

Multi-Wavelength Diagnostics of Cosmic Dust:

From Galactic Dust Clouds to Young Active Galaxies

Ph.D. Dissertation

by

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Abstract

Dust is an ever present part of the universe from carbon emissions on earth to regulation of galactic evolution. Therefore, the investigation and understanding of this dust on various astrophysical scales is vital to the perception of our universe. It is with this in mind that we pursue the inspection of cosmic dust on various scales with the aid of a variety of instruments with observations across the electromagnetic spectrum. The primary focus of my scientific research which is laid out in this thesis is the multi-wavelength inspection of cosmic-dust across the universe.

The first part of this work involved the analysis of set of the most compact Radio Galaxies. We performed a systematic analysis of the mid-infrared (MIR) properties of the youngest radio galaxies, based on low-resolution data provided by the WISE and IRAS satellites. We restrict our analysis to sources with available X-ray data that constitute the earliest phase of radio galaxy evolution, i.e. those classified as Gigahertz Peaked Spectrum (GPS) and/or Compact Symmetric Objects (CSOs) and as such have radio jets on the scale of the dusty taurus and are ideal for studying the interaction of the jets with the surrounding ISM. We found a variety of MIR colors in this sample, and observe that the sources in which the MIR emission is dominated by the ISM component uniformly populate the region occupied by galaxies with a wide range of pronounced ($\geq 0.5M_{\odot} \text{ yr}^{-1}$) star formation activity. We compare the MIR color distribution in our sample to that in the general population of local AGN, in the population of evolved FR II radio galaxies, and also in the population of radio galaxies with recurrent jet activity. We conclude that the triggering of radio jets in AGN does not differentiate between elliptical hosts with substantially different fractions of young stars; instead there is a relationship between the jet duty cycle and the ongoing star formation. The distribution of the sub-sample of our sources with $z < 0.4$ on the low-resolution MIR vs. absorption-corrected X-ray luminosity plane is consistent with the distribution of a sample of local AGN.

The second aspect of my inspection of dust in the universe was the thorough multi-wavelength inspection of a dark cloud just prior to the onset of star formation, DC 314.8–5.1. The target has a serendipitous association with a B-type field star, which illuminates a reflection nebula in the cloud. In our first publication, we focussed on the polycyclic aromatic hydrocarbon (PAH) emission features prevalent throughout the mid-infrared range. The analysis of the spectra with the PAHFIT software as well as pypahdb package, shows that (i) the intensities of PAH features decrease over distance from the ionizing star toward the cloud center, some however showing a saturation at larger distances; (ii) the relative intensities of the 6.2 and 8.6 features with respect to the 11.2 μm feature remain high throughout the globule, suggesting a larger cation-to-neutral PAH ratio of the order

of unity; the breakdown from pypahdb confirms a high ionized fraction within the cloud; (iii) the pypahdb results display a decrease in large PAH fraction with increased distance from HD 130079, as well as a statistically significant correlation between the large size fraction and the ionized fraction across the globule; (iv) the 7.7 PAH feature displays a peak nearer to $7.8\ \mu\text{m}$, suggesting a chemically processed PAH population with a small fraction of UV-processed PAHs; (v) the $\text{H}_2\ \text{S}(0)$ line is detected at larger distances from the ionizing star. All in all, our results suggest divergent physical conditions within the quiescent cloud DC 314.8–5.1 as compared to molecular clouds with ongoing starformation.

In our second publication on this object, we delved into the multi-wavelength observations of the cloud, utilizing archival and targeted observations. In this work I performed a multi-wavelength inspection of the dark globule, DC 314.8–5.1. This work utilizes the Swift Target of Opportunity X-ray observations, we obtained in Fall of 2021, with the original goal of identifying and clarifying the ROSAT source detection that was found in the center of the globule. We find no infrared or x-ray association with the ROSAT source detection, however we find a low significance source in the southern boundary of our globule, likely a compton-thick background AGN. We investigate sources within this globule identifying that the globule is truly pre-starforming with no X-ray, infrared, or optically detected YSO or protostar candidates.

To an initial look these two objects may seem widely unrelated and in some ways this is correct. Dark clouds and globules lie on the low-energy side of astrophysics where active-galactic nuclei and young radio galaxies lie on the high-energy side of astrophysical phenomenon. However, the processes at play in both systems are remarkably similar. We look at the beginning interactions of High-Energy particles with the ISM. Whether it's the energetic particles being injected into the ISM by jets or interactions with cosmic-rays and molecular clouds.

Charakterystyka pyłu kosmicznego w szerokim zakresie widmowym: od obłoków pyłowych Drogi Mlecznej, do młodych galaktyk aktywnych

Pył jest zaskakująco powszechnym składnikiem Wszechświata, którego obecność stwierdzono w różnych układach astrofizycznych, od gęstych obłoków ośrodka międzygwiazdowego na obrzeżach Drogi Mlecznej, aż po jądra aktywnych galaktyk, w których znajdują się supermasywne czarne dziury. Interesująca jest jednak nie tylko sama obfitość kosmicznego pyłu, ale i jego znaczenie fizyczne, gdyż cząsteczki pyłu są ważnym czynnikiem wpływającym na kształtowanie chemii ośrodka międzygwiazdowego, a nawet ośrodka międzygalaktycznego. Dla przykładu, pył osłania mniejsze cząsteczki gazu przed działaniem promieniowania UV, zapewnia powierzchnie czynną dla aktywnej chemii, dominuje fotoelektryczne ogrzewanie gazu, i kontroluje równowagę jonizacyjną plazmy. Mając na uwadze ten szeroki kontekst, w swojej pracy prowadziłam badanie pyłu kosmicznego w różnych wybranych systemach astrofizycznych, używając różnorodnych teleskopów dostarczających dobrej jakości dane w szerokim zakresie widma elektromagnetycznego, jednak głównie skupiając się na podczerwieni.

Pierwsza część mojej pracy obejmowała analizę próbki najmłodszych galaktyk radiowych, w których nowonarodzone zwarte dzety, utworzone w wyniku wzmożonej akrecji na supermasywne czarne dziury, oddziałują bezpośrednio z ośrodkiem międzygwiazdowym galaktyk macierzystych. Wraz z zespołem współpracowników, dla starannie wybranej próbki takich młodych radiogalaktyk przeprowadziliśmy systematyczną analizę danych w zakresie średniej podczerwieni (ang.: “mid infra-red”, dalej MIR), zebranych z wykorzystaniem obserwacji o niskiej rozdzielczości satelity WISE oraz satelity IRAS. W zgromadzonych danych zaobserwowaliśmy szeroki zakres kolorów MIR, z dominującym udziałem albo chłodniejszego pyłu z ośrodka międzygwiazdowego, albo gorętszego pyłu z okołojądrowego rejonu osłaniającego centra galaktyk. W przypadku pierwszej klasy obiektów, obserwowane kolory MIR świadczyły o wyraźnej aktywności formowania się gwiazd w tempie przekraczającym $0.5 M_{\odot} \text{ yr}^{-1}$. Porównaliśmy rozkład kolorów MIR w naszej próbce z rozkładem obserwowanym dla różnych innych typów galaktyk aktywnych, znajdując związek między cyklem aktywności dzetów, a trwającym procesem formowaniem się gwiazd: galaktyki, w których obecność populacji młodych gwiazd jest bardziej wyraźna, zdają się charakteryzować wysoce modulowaną i zazwyczaj krótkotrwałą aktywnością dzetów.

Drugim aspektem moich badań nad pyłem kosmicznym była analiza danych spektroskopowych zebranych przez Kosmiczny Teleskop *Spitzer* dla galaktycznego obłoku pyłowego DC 314.8–5.1, znajdującego się w fazie przed rozpoczęciem epizodu formowania się gwiazd. Obiekt ten stowarzyszony jest z sąsiadującą gwiazdą typu B, która indukuje mgławicę refleksyjną w obłoku. W naszej pracy skupiliśmy się na emisji wielopierścieniowych węglowodorów aromatycznych (ang.: “polycyclic aromatic hydrocarbon”, dalej PAH) dominujących w całym zakresie MIR. Nasze szczegółowe modelowanie spektralne ujawniło, że intensywność struktur PAH zmniejsza się wraz z odległością od gwiazdy jonizującej w kierunku centrum obłoku, jednak w przypadku niek-

tórych struktur ulegając nasyceniu na większych odległościach. Fakt ten można wyjaśnić jako efekt jonizacji wnętrza obłoku przez promieniowanie kosmiczne, w dodatku do fotojonizacji przez sąsiadującą gwiazdę. Ten wniosek został dodatkowo potwierdzony przez zaskakująco duży stosunek kationów do neutralnych PAH odzwierciedlony w obserwowanym stosunku intensywności struktur emisyjnych PAH, a także przez statystycznie istotną korelację między względną wielkością ziaren pyłu a stopniem jonizacji w całym obłoku. Ogólnie rzecz biorąc, nasze wyniki wskazały na odmienne warunki fizyczne charakteryzujące DC 314.8–5.1 w porównaniu z obłokami molekularnymi, w których zachodzi aktywny proces formowania się gwiazd.

W moim trzecim projekcie badawczym przeprowadziliśmy dodatkową analizę DC 314.8–5.1 w szerokim zakresie widma elektromagnetycznego, korzystając z przeglądu optycznego GAIA, przeglądu w bliskiej podczerwieni 2MASS oraz średniej podczerwieni WISE, dedykowanego obrazowania MIR za pomocą Kosmicznego Teleskopu Spitzera, oraz danych rentgenowskich uzyskanych za pomocą teleskopu Swift-XRT. Głównym celem tej analizy było zidentyfikowanie potencjalnych protogwiazd i młodych obiektów gwiazdowych (ang.: “young stellar objects”, dalej YSO) powiązanych z obłokiem. Nasza szczegółowa analiza zebranych danych nie wykazała istnienia żadnych obiektów tego typu, potwierdzając bardzo wczesny etap ewolucyjny systemu. DC 314.8-5.1 stanowi zatem gęsty i zwarty rezerwuar zimnego pyłu i gazu, dający wyjątkową możliwość wglądu w pierwotną formę ośrodka międzygwiazdowego. Brak protogwiazd lub YSO umożliwia w szczególności zdiagnozowanie pierwotnej struktury temperatury pyłu, a także rzetelną charakterystykę oddziaływania obłoku z cząstkami galaktycznego promieniowania kosmicznego. W odniesieniu do tego pierwszego zagadnienia, na podstawie danych satelitarnych w zakresie mikrofalowym *Planck*, oraz dalekiej podczerwieni IRAS, stwierdziliśmy obecność w systemie gorącego pyłu o temperaturach sięgających 200 K, w dodatku do dominującego składnika pyłu na 14 K. W odniesieniu do drugiej kwestii zauważyliśmy, że podczas gdy promieniowanie kosmiczne o stosunkowo niskich energiach może wyjaśnić wspomnianą wcześniej wysoką jonizację obłoku, promieniowanie kosmiczne o wyższych energiach powinno jednocześnie prowadzić do produkcji wysokoenergetycznych neutrin oraz fotonów γ , poprzez rozpad naładowanych i neutralnych pionów powstałych w wyniku nieelastycznych zderzeń promieni kosmicznych z zimnym gazem obłoku.

Podsumowując, w swojej pracy wykazałam iż pył kosmiczny jest niezwykle ważnym elementem diagnostyki wielu procesów astrofizycznych, w tym między innymi: cyklu aktywności relatywistycznych dżetów w aktywnych jądrach galaktyk, interakcji ultrarelatywistycznych promieni kosmicznych z ośrodkiem międzygwiazdowym, i wreszcie wczesnych etapów formowania się gwiazd w obłokach molekularnych.

Contents

Acknowledgments	iii
Abstract	v
1 Introduction	1
1.1 Cosmic Dust	2
1.1.1 Formation and Origins of Cosmic Dust	2
1.1.2 Polycyclic Aromatic Hydrocarbons	4
1.1.3 Cosmic-ray Interactions	7
1.2 Molecular Clouds in Starforming and Active Galaxies	10
1.2.1 Molecular Clouds as Star Formation Nurseries	10
1.2.2 Multi-wavelength View on Dust Clouds	14
1.2.3 Circumnuclear Dust in Active Galaxies	16
2 Mid-Infrared Diagnostics of the Circumnuclear Environments of the Youngest Radio Galaxies	19
2.1 Introduction	20
2.2 Sample Selection	23
2.3 MIR Data Acquisition	25
2.3.1 MIR Data	25
2.3.2 Source Contamination	25
2.3.3 MIR Photometry	27

CONTENTS

2.4	Results & Discussion	30
2.4.1	<i>WISE</i> Colors and Host Galaxy Morphologies	30
2.4.2	MIR/X-ray Correlation	37
2.4.3	Gamma-ray Emitters 1718–649 & 1146+596	40
2.5	Conclusions	42
2.6	Appendix	44
2.6.1	Non-thermal X-ray Emission of Young Radio Galaxies	44
3	Spectroscopic Diagnostics of the Mid-Infrared Features of the Dark Globule, DC 314.8–5.1, with the Spitzer Space Telescope	47
3.1	Introduction	48
3.2	System Overview	49
3.3	Spitzer Observations	52
3.4	Data Analysis	52
3.4.1	Reduction of Data Products	52
3.4.2	Fitting Process for Data Products	54
3.4.3	Extraction of Intensity Maps	56
3.4.4	Extinction Profile	56
3.5	Results	58
3.5.1	Trends & Progressions	58
3.5.2	Individual Features and Lines	58
3.5.3	Dust Continuum	65
3.6	Discussions	68
3.6.1	PAH Ionized Fraction	68
3.6.2	Molecular Hydrogen Detection	72
3.7	Conclusions & Final Remarks	72
4	Multiwavelength Survey of Dark Globule DC 314.8–5.1: Point Source Identification and Diffuse Emission Characterization	75

CONTENTS

4.1	Introduction	76
4.2	Multi-wavelength Overview	77
4.2.1	Archival Low-Resolution Data	79
4.2.2	High-Resolution Data	80
4.3	Identification of YSOs	83
4.3.1	IRAC & 2MASS Source Selection	85
4.3.2	WISE Source Selection	86
4.3.3	Gaia Parallax Measurements	88
4.3.4	Pre-Main Sequence Stars in Swift XRT Data	88
4.4	Discussions	90
4.5	Conclusions	94
4.6	Appendix	95
4.6.1	A: Mid-Infrared Images of DC 314.8–5.1	95
4.6.2	B: ROSAT and Swift XRT Comparison	97
4.6.3	C: IRAC color Cuts by Gutermuth et al. (2009)	98
4.6.4	D: IRAC–2MASS color Cuts by Winston et al. (2019)	99
4.6.5	E: IRAC–MIPS color Cuts by Gutermuth et al. (2009)	100
4.6.6	F: WISE color Cuts by Kang et al. (2017)	100
5	Summary and Future Prospects	103
	References	107

List of Figures

1.1	Dust Coagulation	3
1.2	PAH Structure	5
1.3	PAH Emission Features	7
1.4	CR proton spectrum	9
1.5	Star formation in Molecular Clouds	11
1.6	Illustration of the evolution of YSOs	12
1.7	Dust production and Destruction	13
1.8	Barnard 68	14
1.9	Schematic of AGN	17
1.10	AGN Spectrum	18
2.1	WISE contaminated sources	24
2.2	WISE color-color diagram for compact radio galaxies	26
2.3	SDSS GRI color composite images of compact radio galaxies	28
2.4	PanSTARRS optical images of compact radio galaxies	29
2.5	Super Cosmos UKST images of 1718–649 and 1934–638	30
2.6	WISE color-color diagram comparison of AGN samples	31
2.7	WISE 12 μ m and the intrinsic 2–10 keV luminosities	35
2.8	The infrared and x-ray redshift distribution	39
3.1	RGB image of DC 314.8–5.1	50
3.2	Spectral extraction regions for DC 314.8–5.1	51

LIST OF FIGURES

3.3	Three selected fully fitted spectra	53
3.4	Pypahdb fully fitted spectra	55
3.5	Intensity maps of major PAH features	59
3.6	PAH features over distance	60
3.7	Integrated Power of main PAH features over distance	61
3.8	5.5 – 30.0 μ m spectrum at 0.03 pc projected distance from HD 130079	62
3.9	Spectral fits for select wavelength ranges	63
3.10	Temperature profiles in DC 314.8–5.1	66
3.11	Ionization intensity ratios	67
3.12	Pypahdb ionization and large size fraction over distance	69
3.13	H ₂ S(0) line over distance	71
4.1	IRAS & Planck images of DC 314.8–5.1	77
4.2	Multi-wavelength images of DC 314.8-5.1	78
4.3	Swift-XRT full, soft, and hard band images of DC 314.8–5.1	81
4.4	IRAC color-color selection cuts for SFGs, AGN, shocks, and PAH	84
4.5	IRAC color-color selection for YSOs	85
4.6	WISE color-color cuts for SFGs, AGN, shocks, and PAH	87
4.7	2MASS image of the Swift detected source	89
4.8	SED of DC 314.8–5.1	92
4.9	Spitzer IRAC band maps	95
4.10	WISE maps of the DC 314.8–5.1 region.	96
4.11	MIPS, ROSAT, and XRT comparison maps	97

List of Tables

2.1	MIR properties of X-ray detected CSOs	22
2.2	<i>WISE</i> 2D KS Test Results	32
2.3	IR–Xray 2D KS Test Results	36
2.4	SFRs, IR luminosities, and γ -ray luminosities of 1718–649 & 1146+596	39
3.1	PAH Drude Profiles	57
3.2	Integrated PAH Features	57
4.1	Infrared Source Associations with X-ray Source	90

Chapter 1

Introduction

The Interstellar Medium (ISM) is a mixture of hot and cold gas, comprised primarily hydrogen (70%) and helium (28%) with the remaining 2% comprising all other elements. The main components of the ISM can be broken down into the cold molecular gas, the cold neutral medium (CNM), the warm neutral medium (WNM), the warm ionised medium (WIM), and the hot ionised medium (HIM), with temperatures increasing from 10K in the molecular gas to 10^6 K in the HIM. In this framework, cosmic dust is a major component of the cold molecular gas and the cold neutral medium contributing heavily to the absorption of light; overall “dust” comprises around 1% of the ISM ([Klessen & Glover, 2016](#); [Saintonge & Catinella, 2022](#)).

Cosmic dust although comprising a small fraction of the overall material in the Universe, is still a ubiquitous component of the baryonic matter, and does indeed play a vital role in the ever-evolving dynamics of astrophysical environments. We often look to stars as a primary component of emission in galaxies, however, dust is also a key component in galactic spectral energy distributions (SEDs) and has an influence on emission across a broad range of wavelengths ([Triani et al., 2020](#)). This can be seen in the phenomenon of dust absorbing ultraviolet light from stars (and consequently star formation) and re-emitting it in the infrared, with an estimated $> 30\%$ of energy from starlight being re-radiated by dust into the infrared (see; [Draine, 2003](#), and references therein). In addition to altering the SED, dust can act as a cooling agent for gas, a depletion agent for metals, and a source for the formation of molecular hydrogen; as such, it plays a notable role in the regulation of galactic evolution ([Triani et al., 2020](#)). Here we outline the fundamentals of cosmic dust including: its composition, formation, evolution, and interactions with such systems as radio galaxies and molecular clouds. We begin with the discussion of what is cosmic dust, followed by delving into the relationship between dust and molecular clouds with regards to star formation and followed by its presence in active galactic nuclei.

1.1 Cosmic Dust

1.1.1 Formation and Origins of Cosmic Dust

Dust is an important component of galactic scale (as well as inter-galactic scale) astronomy. However, in order to understand the dust within astrophysical environments one must first determine its origin. This can be done for dust by carefully tracking the metal abundance in galaxies which is the primary raw material for its formation. A fundamental method for the regulation of metallic content in a galaxy is through star formation, and consequently dust in the Universe is understood to mainly be formed in the later stages of stellar evolution, e.g. in stellar-outflows and during supernovae explosions (Triani et al., 2020).

In regards to the production of dust during stellar evolution, lower mass stars will primarily eject metals during their asymptotic giant branch phase through the process of stellar outflows at later stages (Triani et al., 2020). Specifically from here dust can be formed by the condensation of such metals within the stellar ejecta (Draine, 2009). Stellar outflows of evolved stars with cool carbon rich red giants produce solid carbonaceous grains where cool oxygen-rich red giants produce silicate grains (Draine, 2009).

For higher mass stars, they will expel the primary fraction of their metals during either type Ia or type II supernova (SN) explosions (Draine, 2009; Triani et al., 2020). Although SN are known to produce metals and as such dust, there still remains to be any conclusive, observational, evidence of dust grain growth in specifically type Ia SN (Triani et al., 2020). Furthermore, there is currently a lack of consensus on which process is the primary contributor to dust in the Universe. More specifically, although SN produce large amounts of dust, one of the primary destroyers of dust in the ISM occurs in the SN shocks where the high velocities of the ejecta lead to erosion by sputtering as well as grain-grain collisions. This results in what is argued to be a small fraction of dust molecules surviving the SN shocks and progressing to the ISM (see, e.g., reviews by Kataoka et al., 2013; Triani et al., 2020; Kennicutt & Evans, 2012).

Aside from the initial formation of dust grains there are, in addition, several processes that can contribute to dust grain growth. This can extend from complex carbon molecules, such as Polycyclic Aromatic Hydrocarbons (PAHs) which can contain 10s to 100s of carbon atoms, all the way to planetesimals reaching sizes of kilometers (Kataoka et al., 2013). A simplistic approach of dust coagulation, a.k.a. the hit and stick method, has widely been accepted as the primary process for dust growth. In this method dust grains experience growth through low-velocity collisions, see Figure 1.1 panel (a), and is expected to be an early stage of dust growth. This process results in not only the growth of the grains but also reduces dust density. At later stages, when there is a high enough collisional speed to supercede the simple hit-and-stick regime, the dust grains experience a disruption leading to compression, Figure 1.1 panel(b), although this process can also lead to grain disruption. Two additional methods proposed in Kataoka et al. (2013) for grain growth are shown in Figure 1.1 panels (c) and (d), specifically gas compression and self-gravitational compression as

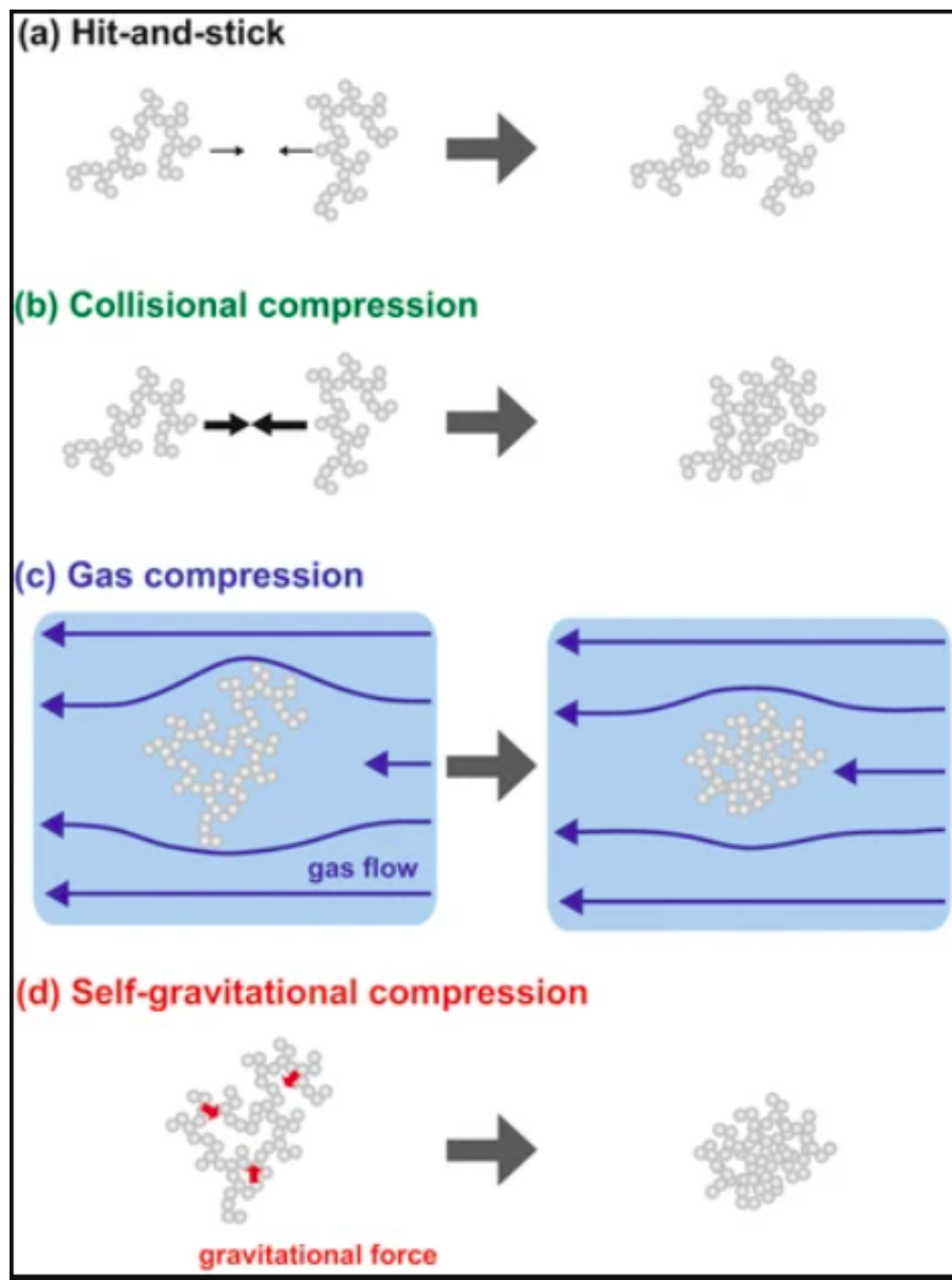


Figure 1.1: Illustration of the subprocesses that can result in coagulation of dust molecules. (a) Two dust aggregates collide to coagulation, which reduces the dust density, and mainly occurs in the early stages of dust growth. (b) Collision of two dust aggregates with higher velocity which compresses the aggregates. (c) Dust aggregate moving with respect to the gas, and it experiences compression due to ram pressure. (d) Large dust aggregates are compressed by their self-gravity. (Figure From: [Kataoka et al. 2013](#))

pathways of static compression and rapid grain growth and as such leading to planetesimals.

The dust grains we are interested in, pre-planetesimal grains, can range in size from 0.35 nm to much larger sizes of $\sim 1 \mu\text{m}$ resulting from these growth processes in the ISM and specifically, molecular clouds (Kennicutt & Evans, 2012). These relatively small dust grains are important for studying the evolutionary processes of their host galaxies. The level of dust within a galaxy can measure the evolutionary stage the galaxy has reached, as well as, dust can regulate the evolution of galaxies through such processes as heating of giant clouds and the formation of molecular hydrogen on the surfaces of dust grains both of which are critical for star formation. Dust can be used to trace physical phenomenons within a galaxy such as the rate of star formation (through the far-infrared emission), can be used to infer the mass of hydrogen, and finally can lead to the reddening of stellar populations and the extinction of stellar light (for a review, see e.g.; Draine, 2003, 2009; Wakelam et al., 2017; Saintonge & Catinella, 2022; Jørgensen et al., 2020).

The chemical makeup of these grains can be primarily carbon grains or silicate grains, however with additional contributions from other metals, as well as hydrogen (as in the case of PAHs; Draine, 2003). Silicate dust grains are expected to contribute a substantial fraction of interstellar dust, although the exact fraction is difficult to estimate with most silicate grains being amorphous and only a small fraction are contained in crystalline material with the primary metallic components being Mg and/or Fe. The other population of dust grains fall under carbonaceous materials, i.e. those with masses dominated by carbon atoms. This category includes many types of molecules including, but not limited to: diamond, graphite, hydrogenated carbon, as well as hydrocarbons both polycyclic aromatic and aliphatic (Draine, 2003). All in all, current observations of dust show us that Mg, Si, Fe and about 2/3 of Carbon reside in dust molecules, Si is primarily amorphous silicate, and there is a large population of PAHs that contain $\sim 10 - 20\%$ of the interstellar carbon in the Milky Way Galaxy and $\sim 4 - 5\%$ of the total grain mass (and other star-forming galaxies Draine, 2009).

1.1.2 Polycyclic Aromatic Hydrocarbons

In the mid-infrared spectrum there exists a plethora of atomic and molecular hydrogen lines, as well as a series of infrared emission lines with the most distinct features at 3.3, 6.2, 7.7, 8.6, 11.3, and $12.7 \mu\text{m}$. These lines for a long time were unidentified and so dubbed “unidentified” infrared emission (UIE) features (Peeters, 2011). These lines always appeared together and were visible in an array of sources from star forming regions to intergalactic medium (see, e.g., reviews by Tielens, 2008; Joblin & Tielens, 2011; Li, 2020). Many hypotheses existed for the originators of these lines, in fact it was (Duley & Williams, 1981) that discovered these bands peak at wavelengths which correspond to the vibrational modes of aromatic material (i.e. hydrocarbons or compounds consisting of carbon and hydrogen). Several carriers were proposed following this such as: Hydrogenated Amorphous Carbon, Quenched Carbon Composites, coal, nanodiamonds, PAHs, and more (Peeters, 2011, and references therein). The criteria which allowed us to identify the carriers

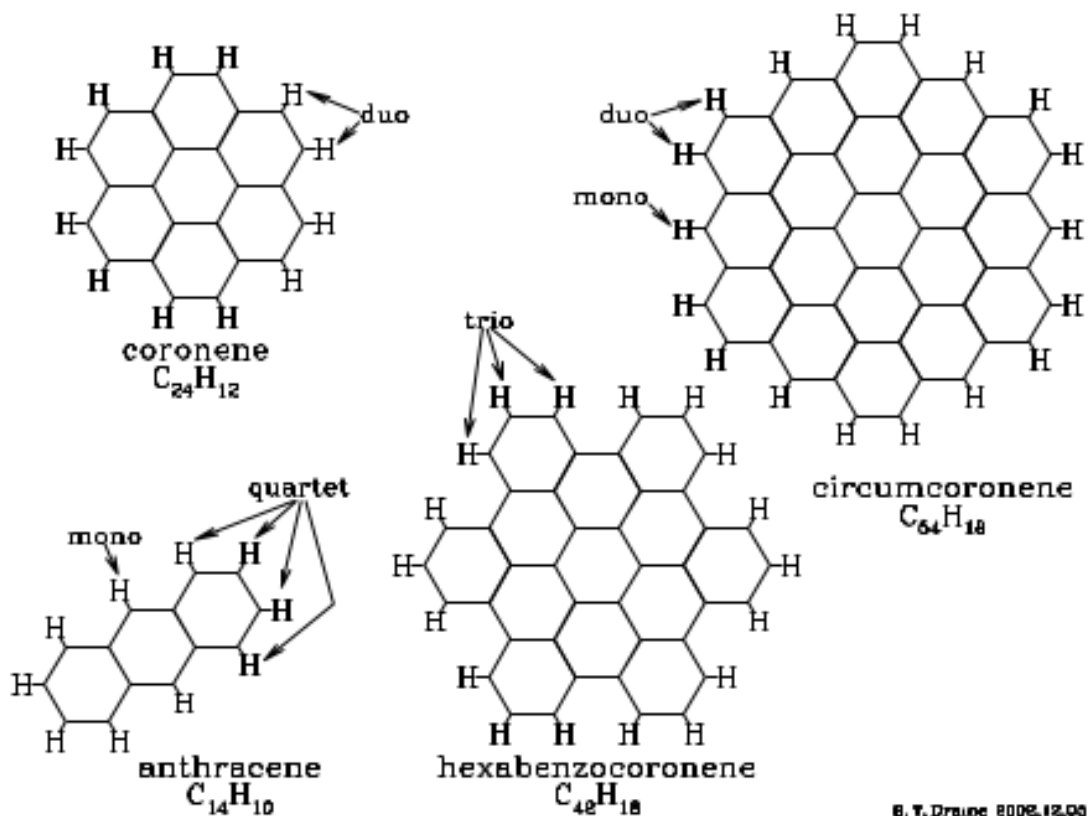


Figure 1.2: Illustration of four different PAH molecules with examples of mono, duo, trio, and quartet Hydrogen cites. (Figure from: [Draine 2003](#))

of these lines was in fact the ubiquitous nature of the emission. These bands were observed in reflection nebula (i.e. there is a star illuminating the interior of a region of dust) and their color temperature is independent of the distance from the star which in this instance most classical dust grains would be too cold to emit in the mid-infrared which means the UIR carriers must be capable of reaching high temperatures even with the absorption of one UV photon ([Peeters, 2011](#)). PAHs were the primary carrier that fit this requirement with their ability to reach temperatures as high as 1000 K upon the absorption of one single UV photon ([Peeters, 2011](#)).

PAHs are molecules containing 10s to 100s of carbon atoms in rings with hydrogens attached to the rings, specifically PAH species contain two or more fused benzene (C_6H_6) rings that arrange themselves in what appears as a honeycomb structure, see [Figure 1.2](#) for an example of four different PAH species ([Peeters & Cami, 2011](#); [Draine, 2003](#); [Salama, 2008](#)). These species are denoted as aromatic due to the bonds the carbon atoms form within their rings. Each carbon atom can have four chemical bonds and are organized in benzene rings which results in each carbon atom being bound to three atoms. Overlapping of remaining orbitals results in a delocalized covalent chemical bonds (π -bonds) which is by definition called an aromatic bond. However, in astronomy often PAHs are referred to as not only these rings but also species including fully or partially hydrogenated

CHAPTER 1. INTRODUCTION

or dehydrogenated molecules, chemically modified –i.e. where one or more hydrogen or carbon atom is replaced by another element such as nitrogen–, and/or metallocomplexes, where a complex is centered on a metal atom or ion). In addition, stacks of PAH molecules like those shown in Figure 1.2, can be used to create larger structures/molecules such as amorphous carbon. PAHs as a population are currently estimated to contribute 10 – 15% of the total interstellar carbon with their emission accounting for 20 – 30% of all the infrared of the Milky Way as well as other star forming galaxies. Although there are many complex types of PAH molecules (i.e.; coronene, hexabenzocoronene) and they are ubiquitous throughout the Universe, astronomical observations have yet to identify a single PAH species due to the fact that the emission bands are connected to vibrational modes which can be present in nearly all species of PAHs (see, e.g., reviews by [Peeters, 2011](#); [Li, 2020](#)).

The primary method of observing PAH species is through their distinctive infrared emission features, such as the primary features at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm , especially since they exhibit similar profiles even among different sources ([Li, 2020](#)). These IR emission lines are a result of the absorption of a far-ultraviolet (FUV) photon by a PAH molecule in the ground state which induces a transition to an excited state which then transitions to a lower state, during which it releases most of its excitation energy as vibrational energy. The molecule cools down primarily through this IR emission from the vibrational modes, until it absorbs another FUV photon. Estimates for the rate of this process are ~ 1 yr in the diffuse ISM, but as rapidly as every 10 minutes in a photodissociation region, see Figure 1.3 for examples of PAH emission in various astrophysical environments ([Peeters & Cami, 2011](#)).

The main PAH features are due to bending and stretching vibrational modes of the bonds within PAH molecules (C-C and C-H bonds). The stretching modes correspond to vibrations from changes in the length between two atoms, and the bending modes correspond to when the angle between two atoms changes with these involving only C-H bonds ([Peeters & Cami, 2011](#)). The 3.3 μm band, specifically, is associated with the Carbon-Hydrogen (C-H) stretching modes, 6.2 and 7.7 μm bands with the Carbon-Carbon (C-C) stretching modes, the 8.6 μm band to the C-H in-plane bending modes, and the 11.3 and 12.7 μm bands to the C-H out-of-plane bending modes ([Li, 2020](#)). In addition to the main features listed above, more recently weaker, secondary features at 15.8, 16.4, 17.1, 17.4, 17.8, and 18.9 μm were discovered, in part due to observations with the Spitzer Space Telescope ([Li, 2020](#)). Because the energy for excitation is similar in all PAH species these modes will show transitions at nearly the same wavelength in all PAH species, and although each species will have its own unique vibrational spectrum due to the common modes overlapping it is not currently possible to distinguish individual molecules in a spectrum ([Peeters & Cami, 2011](#)). It is noted, however, that the features longward of 15 μm are a result of the entire molecule experiencing motion/vibration and can be attributed to specific species or groups of species ([Peeters & Cami, 2011](#)).

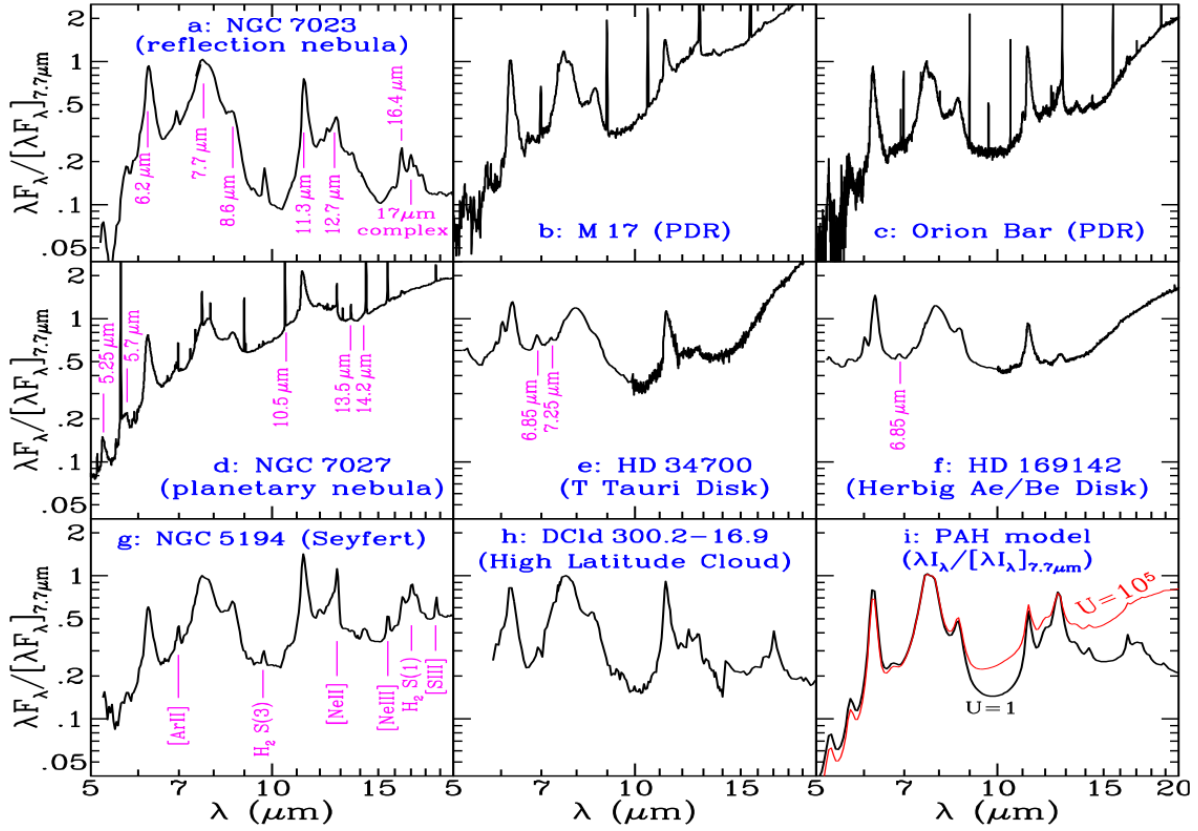


Figure 1.3: Examples of PAH emission in different types of sources with major PAH bands marked in panel (a), with weaker PAH bands marked in panel (d), and the atomic gas lines are marked in panel (g). The types of objects shown are as follows: (a) Reflection nebula, NGC 7023; (b) M17 Photo-dissociation front (PDR); (c) Orion Bar PDR; (d) Planetary Nebula, NGC 7027 ; (e) T-Tauri disk, HD 34700; (f) Herbig Ae/Be disk, HD 169142; (g) Seyfert-type spiral galaxy, NGC 5194; (h) High latitude cloud, DC1d 300.2–16.9; and finally (i) PAH emission model for PAHs illuminated by the local interstellar radiation field. (Figure from: [Li 2020](#))

1.1.3 Cosmic-ray Interactions

Cosmic-rays are energetic particles that permeate the Galaxy, and are isotropic on the sky. Most CRs are atomic nuclei, primarily protons, with helium only amounting to $\sim 10\%$ and heavier molecules and metals only accounting for 1% ([Gabici, 2022](#)). The vast majority of CRs originate within our Galaxy, with only the highest energy particles (with energies exceeding 10^{15} eV) having a possibly extragalactic origin. The origin of Galactic CRs is believed to be predominantly that of a diffusive acceleration at strong shock waves driven by supernova explosions. After escaping their sources, CRs propagate diffusively throughout the ISM, interacting with matter, photon fields, and Galactic magnetic field, losing in this way their energy or even potentially being destroyed in

CHAPTER 1. INTRODUCTION

the process (Tatischeff & Gabici, 2018). Low energy cosmic rays (LECRs), i.e. ≈ 1 GeV, are a prominent source of the ISM ionization and heating; they may also induce magnetohydrodynamical turbulence, as well as provide pressure support for the launching of Galactic wind, and as such are a major contributor in interstellar chemistry and star formation processes. Current observations with instruments such as the *Fermi* Large Area Telescope (LAT) have set constraints on the population of CRs above energies of a few hundred MeV, however, the spectrum of CRs at lower energies is still largely unconstrained (Tatischeff & Gabici, 2018).

Observations of these LECRs show that their relative intensity follows a 11-year periodicity corresponding directly to solar activity, which is referred to as Solar Modulation. Essentially, CRs that originate outside of the solar system on their journey to Earth are impacted by solar wind, which is a flow of magnetised and turbulent plasma extending outward from the Sun. This prevents LECRs from traveling freely into the inner heliosphere, and as such curtails the low-energy end of the CR spectrum, see Figure 1.4 for a representation of the CR spectrum without modulation as well with modulation at various epochs of solar activity, from Gabici 2022. While this effect is significant for LECRs, high-energy CRs are vastly undisturbed by solar activity, and so it is due to this solar modulation that the LECR spectrum cannot be accurately determined with near-Earth observations.

Since LECR cannot be directly observed, we turn to secondary methods, measuring their interactions with matter in the Galaxy, i.e. γ -rays. Observations of γ -rays are much easier as they can travel through large densities of matter without being absorbed, which indeed we see from the significant diffuse γ -ray emission from the Galactic disk. The process resulting in γ -ray emission consists of two steps: a CR proton ($E_{\text{kin}} \geq 280$ MeV) interacts with a proton at rest in the ISM which generates a neutral pion, that subsequently decays into two γ -rays. Furthermore, the γ -rays produced through this decay process will have the same energy which follows to be linked directly to the CR proton energy by $E_{\gamma} \approx 0.1 E_{\text{CR}}$, so each γ -ray produced in this way will have an energy about 10% that of the originating CR (e.g., Dermer, 1986; Stawarz et al., 2010). As such, we can utilize this relationship to extrapolate the CR spectrum down to lower energies.

The emission of γ -rays is not, however, the only astronomical phenomenon resulting from CR interactions within the ISM, and specifically molecular clouds. In addition to γ -ray production, as discussed above, CR interactions can also produce ionization within molecular clouds (Gabici, 2022). The primary agent of photo-ionisation within the ISM is UV emission from hot stars, but high energy UV photons ($\gtrsim 13.6$ eV) are absorbed by interstellar gas and do not propagate far within the ISM. Lower energy UV's propagate further but primarily only ionise carbon. Molecular hydrogen has an ionization potential of 15.4 eV and so is well protected from UV radiation due to the efficient absorption of higher energy UV photons by the ISM. This leaves LECRs as the dominant ionising agent for higher densities. The ionization of H_2 results in the formation of protonated hydrogen, H_3^+ , which triggers a cascade of reactions and molecule formation. It is through observations of this H_3^+ that one can make predictions on the CR ionisation rate within such clouds. Following the formation of H_3^+ , O^+ is produced and through a chain of reactions

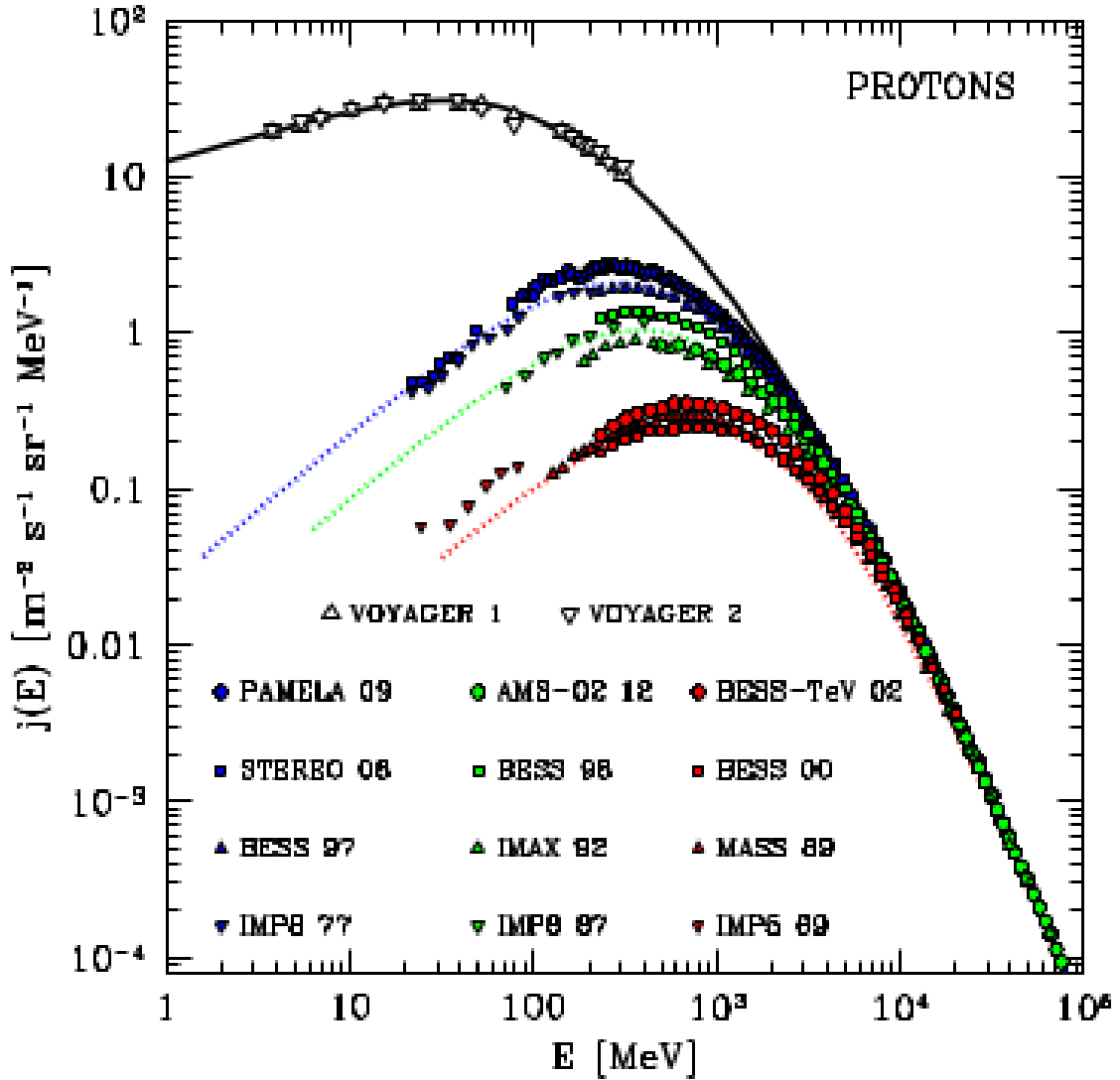


Figure 1.4: Spectrum of CR protons measured by Voyager 1 (white upwards pointing triangles) and Voyager 2 (white downwards pointing triangles) with the black line denoting the modeled, unmodulated CR spectrum. Colored points refer to several epochs of solar activity; red–maximum, green–intermediate, and blue–minimum solar activity with the respective colored dotted lines representing modeled, modulated CR spectrum for modulation potentials at 0.6, 0.8, and 1.4 GeV, respectively. (Figure from: [Gabici 2022](#))

produces several molecules from interactions with H_2 such as, OH^+ , H_2O^+ , and H_3O^+ , with the first two products dominating dense molecular clouds. These products as well as the ionisation of PAH molecules are proposed as methods to further measure the CR ionisation rate within the ISM ([Padovani et al., 2020](#); [Fujita et al., 2021](#)).

1.2 Molecular Clouds in Starforming and Active Galaxies

The nomenclature surrounding clouds is non-uniform with many similar systems having many different names such as: molecular cloud, dark cloud, dust cloud, dark globule, dark nebula, etc, with very little distinction between these so-called classes. We note here the primary distinction in cloud nomenclature is that interstellar clouds are cold but relatively low density where as molecular clouds are dense and contain molecular hydrogen, however, apart from this distinction there is no defined difference between the additional names stated here and in literature.

1.2.1 Molecular Clouds as Star Formation Nurseries

Molecular clouds are dense regions of the interstellar medium dominated by molecular hydrogen (H_2) (Jørgensen et al., 2020). They are host to a plethora of chemical compounds such as PAH species, and other organic compounds; the evolution of which is strongly dependent on the evolution of the clouds themselves and the development of star formation within. In fact it is the shielding provided by high column densities which allows the fraction of H_2 and CO to become large in such regions where in lower densities their quantities would be greatly curtailed by photo-dissociation. It follows that the introduction of star formation within such an environment would greatly alter this balance, and as such in order to understand the star formation process it is vital to also understand the host regions themselves (a.k.a. molecular clouds) (for a review, see e.g.; Klessen & Glover, 2016; Jørgensen et al., 2020).

The simplest models for cloud formation is the coagulation method, much like the coagulation discusses above for specific PAH molecules, in which small atomic clouds are formed from warmer atomic gas through thermal instability and collisions between small clouds dissipate energy and as such tend to coagulate forming larger clouds. Eventually clouds become large enough to have self-shielding protecting themselves from the effects of the interstellar radiation field and as such are able to obtain large quantities of molecular compounds. This process can continue until clouds have reached massive sizes and begins to be disrupted once star formation begins in the interiors of such systems. Although this model is attractive with its simplicity it does not fully explain the formation of massive molecular clouds as the timescales for the coagulation method to form a cloud with mass of $10^5 - 10^6 M_\odot$ is of the order of 100 Myr, possible extending to even longer timescales. Typical giant molecular clouds only have expected lifetimes of an order of magnitude lower, and as such –with the exception of clouds within the spiral arms of the Galaxy which experience a higher rate of collisions– does not explain the presence of giant molecular clouds at high galactic latitudes (Klessen & Glover, 2016).

A secondary model for cloud formation is the so-called converging flow model which argues that molecular clouds form in dense, post-shock regions formed from converging flows of gas. In these flows, gas collides, and through thermal instabilities form denser, cooler gas much more rapidly than the aforementioned method (Klessen & Glover, 2016). However, it remains unclear

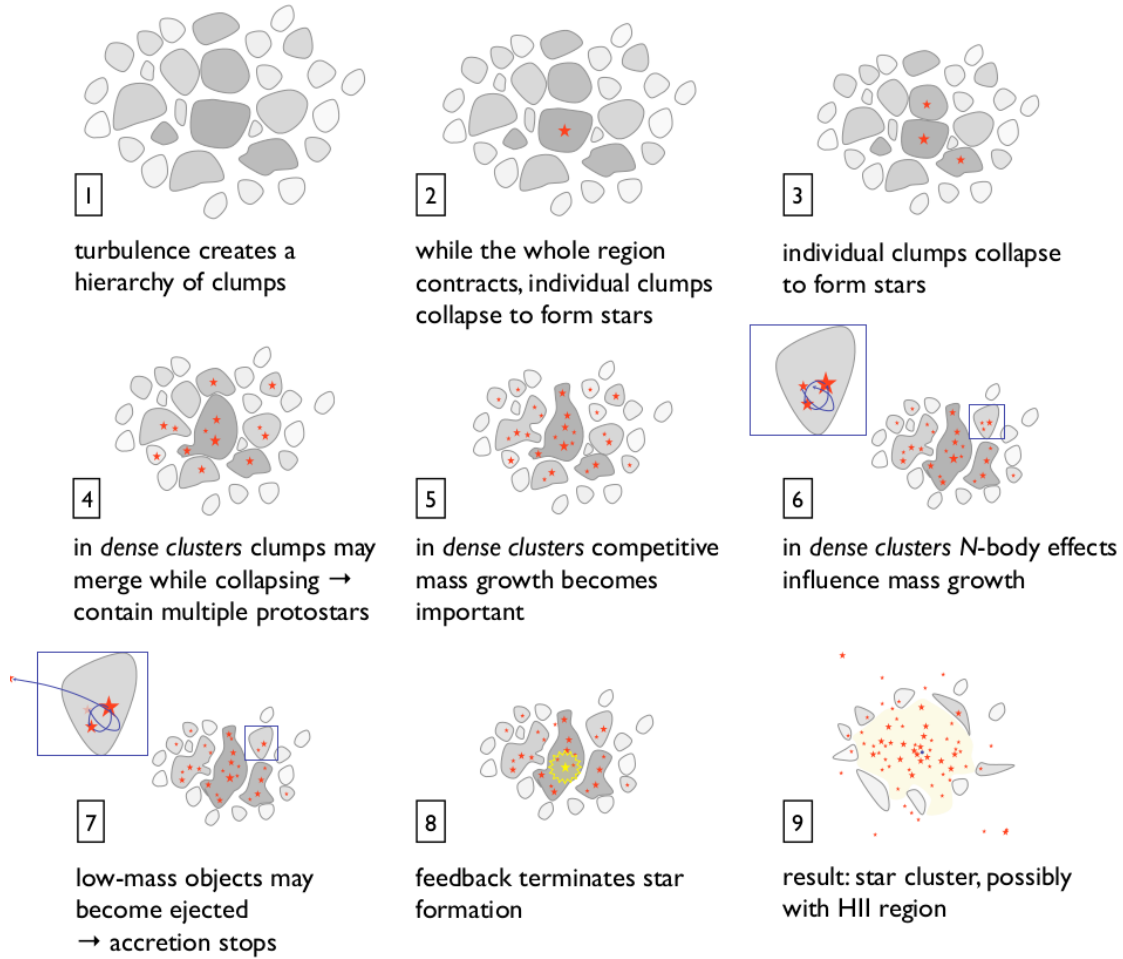


Figure 1.5: Schematic breaking down the steps involved in the formation of individual stars and clusters within a dense molecular cloud. (Figure from: [Klessen & Glover 2016](#))

which processes dominate cloud formation and evolution from diffuse atomic gas.

However, as these clouds evolve their structures further develop with denser regions forming filamentary like structures, as seen by the Atacama Large Millimeter/sub-millimeter Array (ALMA) with cores or clumps forming overdensities within these filaments. Star formation within these dense molecular clouds occurs within giant molecular cloud “clumps” that form stellar clusters, as well as in smaller molecular cloud “cores” forming single or binary star systems (see; [Jørgensen et al., 2020](#); [Robitaille et al., 2020](#); [Kennicutt & Evans, 2012](#)).

The star formation process is triggered primarily by gravitational collapse of these dense cores and clumps, Figure 1.5 shows an illustration of this process within a molecular cloud. Large scale galactic structures such as spiral arms, black hole activity, SN explosions, stellar winds, photo-ionisation and radiation pressure feedback, can effect the timescale of collapse. These processes are, of course, much longer than can be observed in a human lifetime, and as such much of our

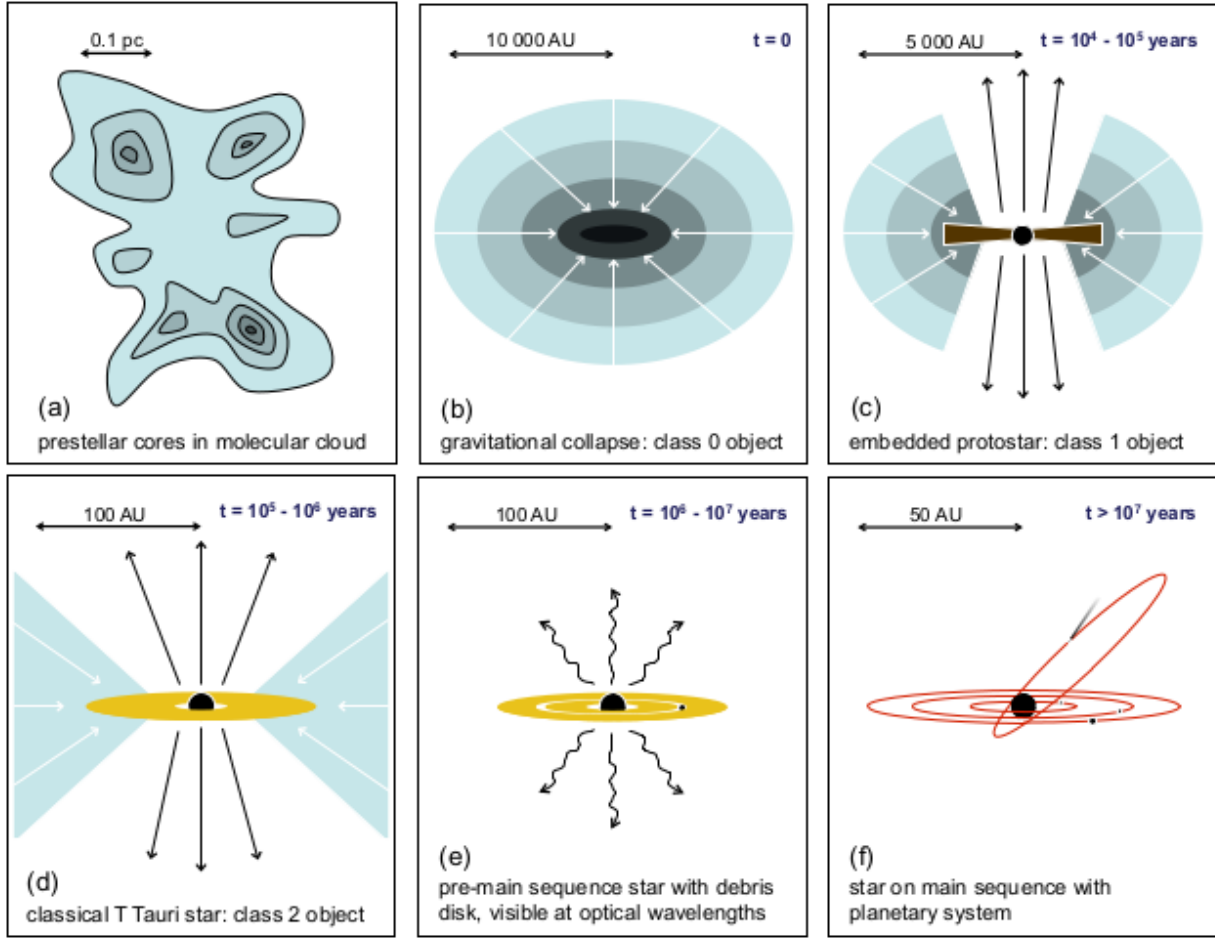


Figure 1.6: Illustrative schematic of the evolution of young stellar objects from prestellar cores (a) through Class 0-III YSOs (b)–(d) and finally pre-main sequence star (e) and main sequence star with a planetary system (f). (Figure from: [Klessen & Glover 2016](#))

knowledge is based on assumptions from viewing clouds at what is assumed to be differing stages of evolution ([Andre et al., 2000](#); [Chevance et al., 2020](#)).

For Sun-like stars, formation occurs in regions of very low temperature (~ 10 K) with densities in these regions of $\sim 10^3 - 10^4 \text{ cm}^{-3}$. These environments are often the dense cores of molecular clouds, where the molecules within the cloud collide and over time build more complex molecules, as discussed above. Stars will form when the dense cores of these clouds collapse, infall of material results in the gravitational potential energy heating the material and increasing densities even up to $\sim 10^8 - 10^9 \text{ cm}^{-3}$ ([Jørgensen et al., 2020](#)). This process continues as the system is altered and disrupted by the evolving young star.

Young stellar objects (YSOs) can be reduced into three main stages I–III. The fundamental characteristic which dominates a young stellar object is its initial mass, see Figure 1.6 to see and illustration of the evolutionary development for a young stellar objects from prestellar cores to main

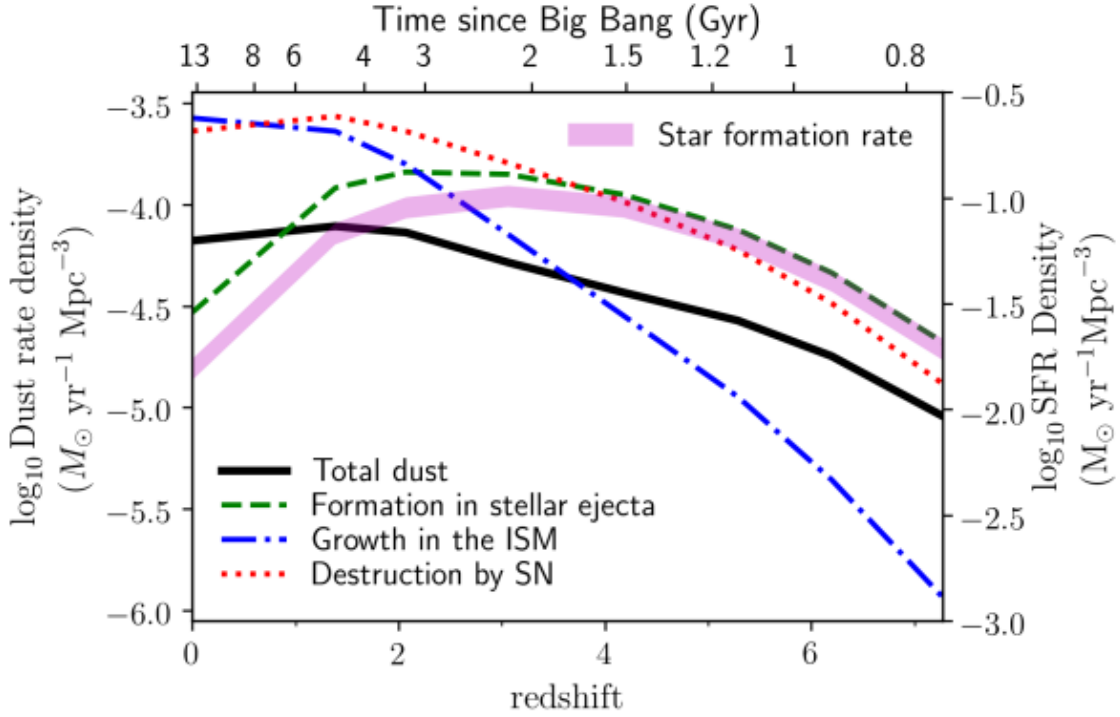


Figure 1.7: The rate of dust production and destruction mechanisms within the ISM as a function of redshift and time, beginning at the time since the Big Bang. (Figure from: [Triani et al. 2020](#))

sequence stars ([Klessen & Glover, 2016](#)). Class I sources denote YSOs that are protostars with infalling envelopes and are characterized by a rising or flat mid-infrared spectrum. Class II denoting pre-main sequence stars with optically thick disks and a decreasing MIR spectrum. Finally, Class III sources have very little infrared excess, and are notoriously difficult to separate from young main-sequence stars. We also discuss here the so-called “transition disk” objects which are YSOs without an inner disk but containing an optically thick outer disk (see in this context, e.g., [Greene et al., 1994](#); [Lada, 1987](#); [Gutermuth et al., 2009](#); [Kang et al., 2017](#)).

The interactions of these young stellar objects with their host clouds is extensive, the main effects of stellar formation is the processing of the dust within the cloud, the disruption of the cloud structure, and heating of the cloud material ([Strom et al., 1975](#)). All in all, star formation and evolution (including supernova) act as a primary feedback process in the dust context of the interstellar medium and in molecular clouds, to see the rate of the creation and destruction of dust in the ISM, as a function of redshift, see Figure 1.7 ([Triani et al., 2020](#)).

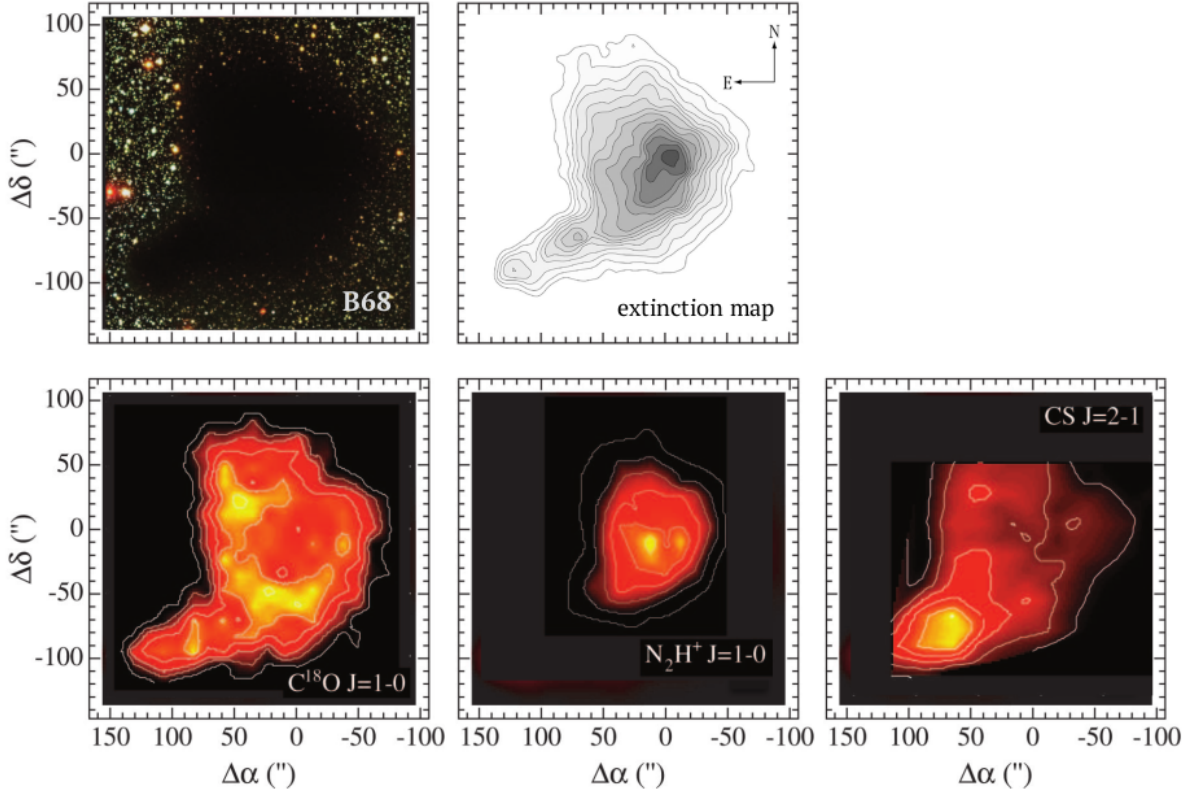


Figure 1.8: Multi-image of the isolated pre-stellar molecular cloud, Barnard 68. Upper panels: (left) the optical image and (right) the extinction map in the optical band. Lower panels: Maps of the emission lines from (left) C^{18}O , (middle) N_2H^+ , and (right) CS . Each image presents the same region of the sky, illustrating the effects of grain depletion in the central regions with higher densities. (Figure from: [Klessen & Glover 2016](#))

1.2.2 Multi-wavelength View on Dust Clouds

Molecular clouds can be defined, simply, as structures in the ISM that are “separate” from their surroundings and represent the coldest and densest part of the ISM. This separation can be done to a rapid change in a physical property, i.e. pressure, surface density, or chemical state ([Kennicutt & Evans, 2012](#)). They are often distinguished by the detection of the lower rotational transitions of CO , as well as the presence of some optical extinction of background stars. Molecular clouds are surrounded by atomic envelopes with a transition region where one can find molecular hydrogen, but atomic carbon. This transition region is referred to as a photo-dissociation region (PDR).

One method of detecting molecular clouds is visible wavelengths, in which there appears to be a reduced density of stars, due to the absorption of the starlight by the dust in these clouds ([Kennicutt & Evans, 2012](#)). In order to identify clouds, one can utilize the star counting method which surveys a given region of the sky for dips in the average stellar density, such as in [Hartley](#)

[et al. \(1986\)](#) which performed such a study on the southern sky to identify 1101 dark clouds. In conjunction, one can utilize the presence of certain compounds to trace clouds and their structure (e.g. CO, HCN). CO is one of the most commonly used tracers for dust, even though H_2 is much more abundant. CO has strong lines that are easy to observe where as H_2 although more abundant, is much less massive and as such requires high temperatures to excite, and so large amounts of H_2 in molecular clouds are not in fact observable. Observations of CO emission or absorption can be used to define the boundaries of clouds. Figure 1.8 shows an example of such detection methods illustrating the optical extinction (and extinction map) as well as the (bottom-left) C^{18}O , (bottom-middle) N_2H^+ , and (bottom-right) CS emission lines, each of which highlighting different structures within the cloud. Furthermore, the reddening of stars along the line of sight through a cloud can be utilized to determine distance measurements and produces distance measurements with a $\lesssim 10\%$ error ([Kennicutt & Evans, 2012](#); [Schlafly et al., 2014](#); [Foster et al., 2012](#), and references therein). There have been many catalogs searching for clouds in this way, and as such, [Dutra & Bica \(2002\)](#) compiled a master catalog from 21 separate dust cloud catalogs to create a master list of 5004 dust clouds in the Milky Way Galaxy with a large fraction of the dust clouds in the Milky Way Galaxy lying within 30 degrees of the Galactic plane, with a small fraction ($\sim 10\%$) lying at high Galactic latitudes.

An advancement in characterizing galactic molecular clouds is the Planck Catalogue of Galactic Cold Clumps (PGCC; [Planck Collaboration et al., 2016b](#)), which detects the low-temperature dust that compromises such clouds in millimeter wavelengths. PGCC is an all-sky catalogue first made available in 2011 providing measurements and maps in bands ranging from 857 – 30 GHz. The catalog contains 13188 sources across the whole sky, and unlike the star counting method the Planck catalog is not biased by the presence of background stars, and in addition provides physical characteristics of the system such as mass, size, mean density, and luminosity ([Planck Collaboration et al., 2016b](#)). Higher resolution millimeter instruments such as ALMA, which provides high resolution and high sensitivity imaging, can provide a deeper look into the structure of molecular clouds, tracing the filaments of dust within the clouds ([Jørgensen et al., 2020](#)).

WISE is an all-sky survey mission covering the entirety of the northern and southern hemispheres which measures the sky in four bands (W1–W4) centered at 3.4, 4.6, 12, and 22 μm , with the corresponding resolution of $6''.1$, $6''.4$, $6''.5$, and $12''$, respectively ([Wright et al., 2010](#)). WISE can be used to not only observe dust within molecular clouds, but also identify young stellar objects and reddened field stars (see in this context, e.g., [Greene et al., 1994](#); [Lada, 1987](#); [Gutermuth et al., 2009](#); [Kang et al., 2017](#)). In the mid to far-infrared the Infrared Astronomical Satellite (IRAS), provides fluxes in four additional bands 12 μm , 25 μm , 60 μm , and 100 μm ([Hetem et al., 1988](#); [Bourke et al., 1995](#)). The IRAS measurements of molecular clouds can detect slightly warmer components of the dust not picked up by the PLANCK observations ([Bourke et al., 1995](#)).

A secondary source of signal from molecular clouds is the absorption of energy by the dust at short wavelengths and the re-emission of that energy at longer wavelengths. Often this is in the form of absorption UV light from stellar populations and the emission of such light into infrared

bands, which can relate physical conditions within the system, see Section 1.1.2. As discussed in more detail above, this process can apply to very high energy as well and result in emission of radio through gamma-ray signatures of such systems as well (see; Gabici et al., 2009; Dermer, 1986; Tatischeff et al., 2012; Nobukawa et al., 2018). In summary, lower-energy cosmic rays ionize the cloud’s interiors, and may produce signatures such as the 6.4 keV iron $K\alpha$ line X-ray emission (see in this context, e.g., Tatischeff et al., 2012; Nobukawa et al., 2018). While lower-energy cosmic rays provide excess ionization in the globule, the higher-energy cosmic rays (not yet into the ultra-high energy regime) should, at the same time, produce high-energy neutrinos and γ -rays, through the decay of charged and neutral pions following from inelastic cosmic ray collisions with the cold gas of the cloud (e.g., Dermer, 1986). In the radio spectrum, molecular clouds present a soft constant emission due to the interactions with background CRs which does not vary greatly with time (Gabici et al., 2009).

All in all, there are a plethora of multi-wavelength signatures of molecular clouds from radio to γ -rays which can be traced with all sky surveys such as Fermi-LAT and the WISE All sky catalog.

1.2.3 Circumnuclear Dust in Active Galaxies

Active galaxies are defined as galaxies containing a super-massive ($\geq 10^6 M_\odot$) black hole in their center that has active gas accretion, referred to as an active galactic nuclei (AGN) (Ho, 2008). AGN can be comprised of the following components: (i) an accretion disk with hot corona; (ii) the broad-line region (BLR) comprised of high density, gas clouds (dust free) moving at large velocities at distances of 0.1-1 pc from the black hole; (iii) a central torus of dusty gas with distances of 0.1-10 pc from the black hole; (iv) a narrow line region comprised of lower density, lower velocity ionized gas which extends from outside the torus to distances as large as thousands of parsecs; (v) a very thin molecular maser disk similar in size to the torus, and (vi) radio jets of varying size. Here we further discuss a central component of AGN, the dusty torus, for recent reviews focused on the AGN tori, see Netzer 2015 and Hickox & Alexander 2018; in addition see also Figure 1.9 for a schematic of these regions within the AGN structure and Figure 1.10 for the respective spectral components of these regions.

In all the AGN unification schemes and diagrams for AGN structure, circumnuclear dusty tori are indeed the essential ingredient. AGN dusty tori are optically thick, hot ($\sim 10^3$ K), forming in the first approximation donut-shaped structures, although more recently a consensus has been reached that they are not uniform but instead very “clumpy” (Nenkova et al., 2008). It is in this torus that it is believed complex dust molecules such as PAHs may reside. In these volatile systems, it was originally thought that PAHs could not survive but recent study has shown observations of PAH populations as near as 10 pc from a central AGN component. The only caveat, in observations of AGN, is that the PAH emission can be diminished by the strong underlying AGN continuum and as such difficult to detect (see in this context, Li, 2020).

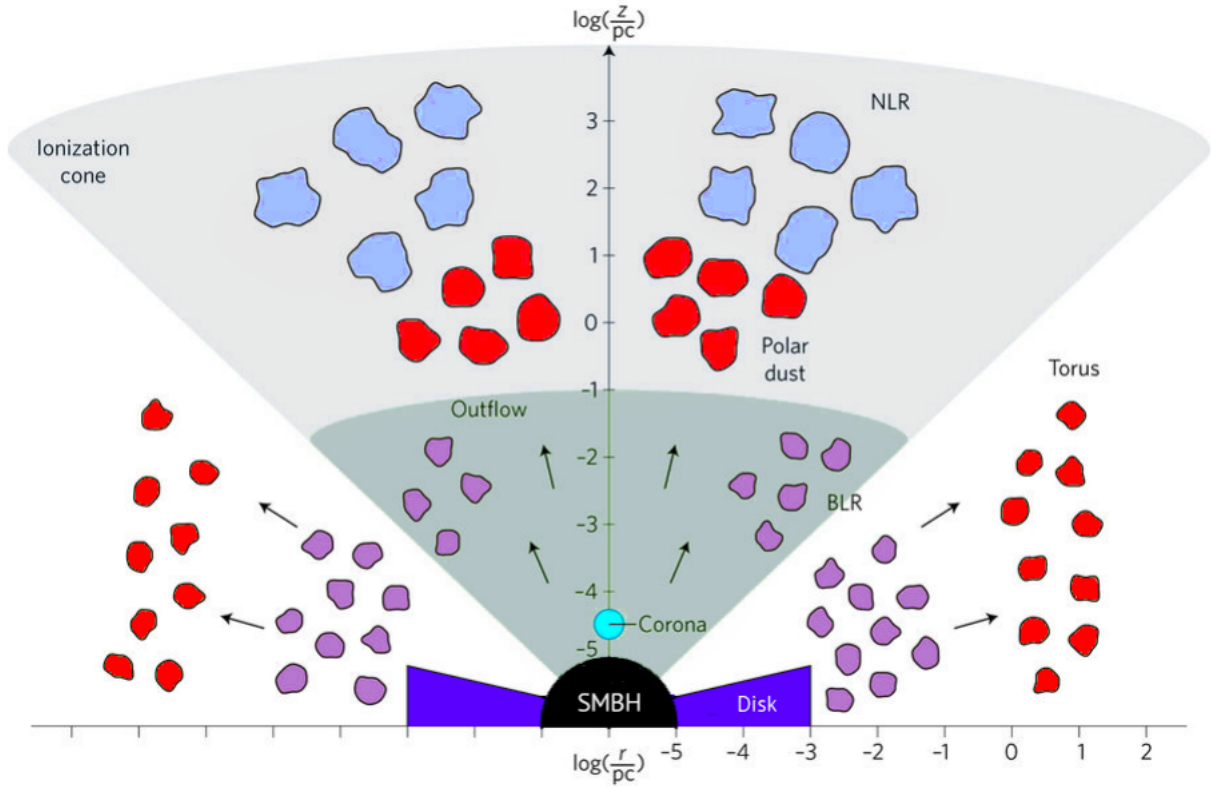


Figure 1.9: Schematic of the AGN physical model, showing key regions around the supermassive black hole. Including the accretion disk (blue regions), corona (turquoise circle), the broad-line region (purple clumpy region), the dusty torus (red clumpy region), and the narrow line region (light blue clumpy region). (Figure from: [Hickox & Alexander 2018](#))

Furthermore, in this context, an obscured AGN is one in which the disk emission passes through the tori, which absorbs the optical, UV, and soft X-ray emission of the disks and disk coronae, before reaching the observer ([Netzer, 2009](#); [Hickox & Alexander, 2018](#)). It is due to the overall dusty nature of most obscuration that selection of obscured AGN can be performed utilizing infrared observations. Selections of such sources can be done through the detection of red UV, as well as utilizing optical and infrared colors to select out galaxies with excess infrared emission. These selections have been greatly improved, in part, due to all-sky surveys such as WISE which allows the inspection of the colors of a large sample of galaxies with relative ease (see in this context, e.g., [Wright et al., 2010](#); [Stern et al., 2012](#); [Mateos et al., 2012](#)). In addition to the infrared and optical colors, the detection of high nuclear extinction from spectral analysis or optical-IR SED fitting can denote an obscured AGN as well as the detection of solid-state absorption features in the mid-IR spectrum, in particular, the Si features at 9.7 and $18\,\mu\text{m}$ see [Hickox & Alexander \(2018\)](#) and in the context of young radio galaxies see [Willett et al. \(2010\)](#). All in all, the absorption of UV and optical light can be seen as an excess in IR lines or continuum emission. In addition, X-ray absorption, reflection and emission can be present in such obscured AGN as well. Specifically, the

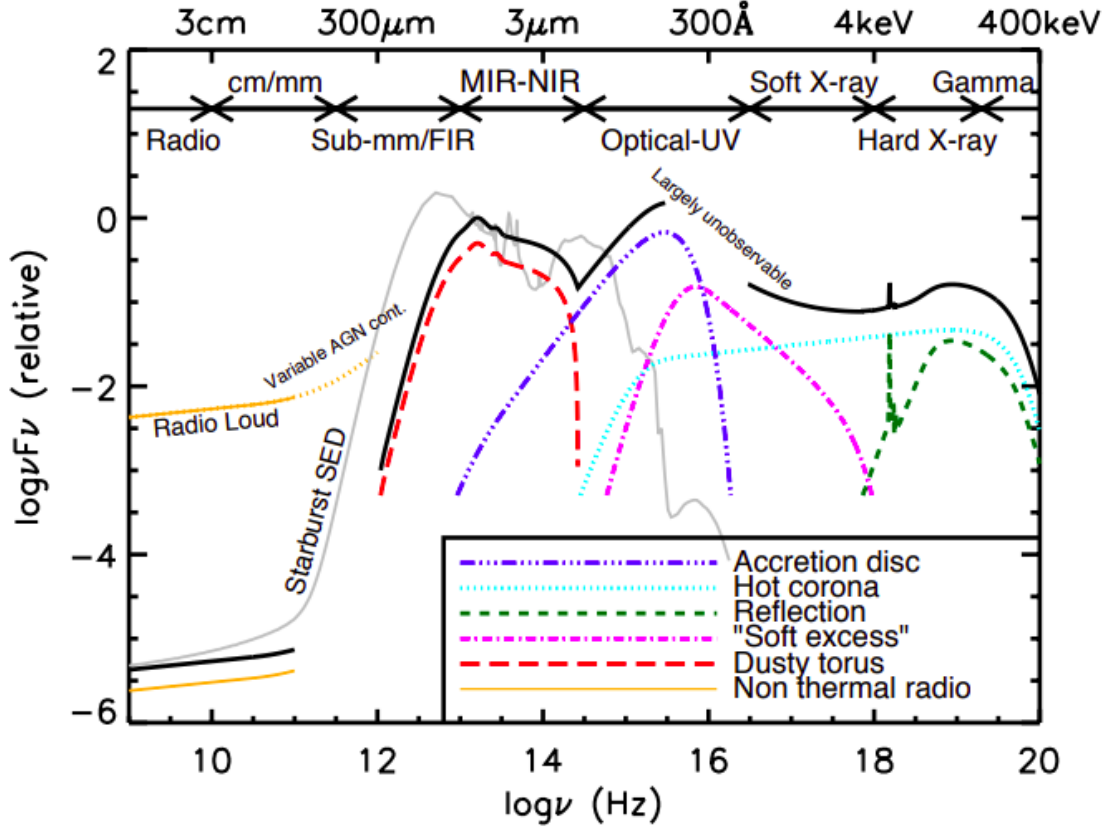


Figure 1.10: Illustration of the AGN spectral components across the electromagnetic spectrum, compared with the SED of a starburst galaxy displayed as the light gray curve, with the thick black curve denoting the total AGN SED with the colored components breaking down the main physical components of the AGN. (Figure from: [Hickox & Alexander 2018](#))

excess emission at 20 keV is a result of the down-scattering of hard X-ray photons from interactions with the dusty torus. Furthermore, the reflection of X-rays off of electrons in a highly ionized gas is a signature of emission passing through the torus as well as such interactions can result in the presence of the K_{α} line of iron at 6.4 – 7.0 keV where the equivalent width of the iron line can directly be related to the level of obscuration ([Netzer, 2015](#)).

Moreover, the central AGN can also influence the dust not only in the torus but the host galaxy itself. The radiation of the central AGN can extend into the host galaxy causing heating and ionization within the ISM. To further study this effect, it is of interest to inspect the youngest and most compact of radio galaxies to see the effects of this ionization at its onset (see in this context, e.g., [Willett et al., 2010](#); [Heckman et al., 1994](#); [Fanti et al., 2000](#); [Tadhunter et al., 2011](#); [Dicken et al., 2012](#)). This effect on the host galaxy could possibly being linked to later epochs of star formation activity ([Netzer, 2015](#); [Hickox & Alexander, 2018](#)).

Chapter 2

Mid-Infrared Diagnostics of the Circumnuclear Environments of the Youngest Radio Galaxies

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Abstract

We present a systematic analysis of the mid-infrared (MIR) properties of the youngest radio galaxies, based on low-resolution data provided by the *WISE* and *IRAS* satellites. We restrict our analysis to sources with available X-ray data that constitute the earliest phase of radio galaxy evolution, i.e. those classified as Gigahertz Peaked Spectrum (GPS) and/or Compact Symmetric Objects (CSOs). In our sample of 29 objects, we find that the host galaxies are predominantly red/yellow ellipticals, with some of them displaying distorted morphology. We find a variety of MIR colors, and observe that the sources in which the MIR emission is dominated by the ISM component uniformly populate the region occupied by galaxies with a wide range of pronounced ($\geq 0.5 M_{\odot} \text{ yr}^{-1}$) star formation activity. We compare the MIR color distribution in our sample to that in the general population of local AGN, in the population of evolved FR II radio galaxies, and also in the population of radio galaxies with recurrent jet activity. We conclude that the triggering of radio jets in AGN does not differentiate between elliptical hosts with substantially different fractions of young stars; instead there is a relationship between the jet duty cycle and the ongoing star formation. The distribution of the sub-sample of our sources with $z < 0.4$ on the low-resolution MIR vs. absorption-corrected X-ray luminosity plane is consistent with the distribution of a sample of local AGN. Finally, we comment on the star formation rates of the two γ -ray detected sources in our sample, 1146+596 & 1718–649.

2.1 Introduction

Compact radio sources constitute a particularly interesting, yet diverse, class of active galactic nuclei (AGN), with newly born radio structures (jets and lobes) fully confined within their host galaxies (see [O’Dea, 1998](#), for a review). As such, they provide direct insight into the mechanisms that lead to triggering the production of relativistic jets in AGN (e.g., [Czerny & You, 2016](#)), as well as insight into the complex dynamics of feedback between evolving supermassive black holes and interstellar medium (e.g., [Tadhunter, 2016](#); [Wagner et al., 2016](#)).

To study these dynamics, specific evolutionary models for compact radio galaxies have been developed (e.g., [Kawakatu et al., 2008](#)), and certain predictions have been made regarding their multi-wavelength emission and absorption properties (e.g., [Stawarz et al., 2008](#)). These models have been tested against various multi-frequency datasets ([Ostorero et al., 2010](#); [Migliori et al., 2014](#)). There, however, still remains a lack of consensus on the relative contribution from jets and lobes, accretion disks and circum-nuclear dusty tori, or, to some extent, the interstellar medium (ISM) itself, to the observed radiative output of such systems at infrared, X-ray, and γ -ray photon energies.

In this context, we focus on a systematic investigation of the mid-infrared (MIR) properties of the most compact radio galaxies. These sources are confirmed spectroscopically in the radio domain as ‘GHz-peaked spectrum’ (GPS) sources, and/or morphologically (using high-resolution radio interferometers) as ‘compact symmetric objects’ (CSOs). In order to study the MIR properties, we utilize data provided by the Wide-field Infrared Survey Explorer (*WISE*), as well as archival data from the Infrared Astronomical Satellite (*IRAS*) augmented in a few cases by *Spitzer* Space Telescope observations. We restrict our sample only to those objects which have been observed in X-rays with either the *XMM-Newton* or the *Chandra* X-ray Observatory, so that multi-wavelength diagnostics can be applied to disclose the origins of the observed fluxes.

Previously, the infrared emission of GPS/CSOs had been analyzed by [Heckman et al. \(1994\)](#) in the mid-far infrared domain, based on low-resolution data from *IRAS*, and by [Fanti et al. \(2000\)](#) in the far infrared, using the Infrared Space Observatory (ISO) data. These authors argued that the mid-to-far infrared emission of compact radio galaxies is comparable to that of the extended radio galaxies with matching radio powers and redshifts. Therefore, these sources are most likely dominated by an AGN component, the hot dusty tori in particular.

More recently, [Willett et al. \(2010\)](#) presented the MIR observations of eight nearby CSOs (redshifts $z \lesssim 0.1$) from *Spitzer*, finding a diversity in their spectral properties. An overwhelming majority of the sources in their sample displayed a contribution from both circum-nuclear dust, heated by the central AGN, and star formation activity within the host galaxy. [Willett et al. \(2010\)](#) argued, moreover, that the star formation rates in the studied sources, estimated at the level of $(0.3 - 50) M_{\odot} \text{ yr}^{-1}$ based on the detected polycyclic aromatic hydrocarbon (PAH) emission, implies a close link between the triggering of radio jets and galaxy mergers. On the other hand, [Tadhunter](#)

et al. (2011) and Dicken et al. (2012) proposed that the enhanced star formation activity in compact radio sources over that observed in evolved radio galaxies, indeed seen in their flux limited samples, may be instead due to an observational selection effect. This follows from the enhanced radiative efficiency of compact radio-emitting jets and lobes in the former class of objects (see also O’Dea, 2016, for the discussion).

In the X-ray domain, the first dedicated studies of GPS/CSOs with the high-angular resolution telescopes *XMM-Newton* and *Chandra*, have been reported by Guainazzi et al. (2004, 2006); Vink et al. (2006); Siemiginowska et al. (2008); Siemiginowska (2009); Siemiginowska et al. (2016); Tengstrand et al. (2009), and Sobolewska et al. (2019b,a). Since the radio structures of the targeted sources remain unresolved even on arcsec scales, various origins of the detected fluxes within the 0.1–10 keV range have been considered by these authors including: accretion disk coronal emission, jet/lobe non-thermal radiation, as well as emission of hot gas within the ISM, modified (shocked) by expanding compact radio structures.

In most cases, unfortunately, rather limited photon statistics preclude any more in-depth spectral modeling, which would enable a robust discrimination between various emission models. The X-ray continua of compact radio galaxies were typically found to be consistent with a single power-law, with photon indices $\Gamma \sim 1 - 2$, moderated by hydrogen column densities $N_{\text{H}} \lesssim 10^{22} \text{ cm}^{-2}$. Such spectra could be accommodated by either the disk coronal emission scenario, with modest intrinsic absorption, or the model in which observed X-ray fluxes are dominated by inverse-Comptonization of various ambient photon fields (and the infrared emission of circumnuclear dusty tori in particular) within compact radio lobes shining through the ISM of host galaxies (Ostorero et al., 2010). Only in a few cases, subjected to deeper exposures (1404+286, 1511+0518 and 2021+614), was there a detection of the neutral fluorescence iron line and/or hydrogen column densities in excess of 10^{23} cm^{-2} , indicating the disk coronal emission is seen through a Compton-thick circumnuclear tori (Guainazzi et al., 2004; Siemiginowska et al., 2016; Sobolewska et al., 2019b,a). On the other hand, for the particular case of 1718–649, the observed X-ray emission appeared contributed to by a hot, collisionally ionized gas located within the central parts of the host galaxy (Siemiginowska et al., 2016; Beuchert et al., 2018).

Below, in Section 2.2 we discuss the selection of the sample including the most compact radio galaxies observed in X-rays. In Section 2.3 we describe the MIR data acquisition for the selected sources, specifically the *WISE*, *IRAS*, and *Spitzer* archival observations. In Section 2.4 we discuss the results of our analysis, and our main conclusions are outlined in Section 2.5. Throughout the paper we assume modern Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{m}} = 0.3$, and $\Omega_{\Lambda} = 0.7$.

Table 2.1. MIR properties of X-ray detected CSOs

Name	z	d_L [Mpc]	LS [pc]	class	W1-W2 [mag]	W2-W3 [mag]	WISE color	IRAS $L_{12\mu m}$ [10^{43} erg/s]	MIPS $L_{24\mu m}$ [10^{43} erg/s]	WISE $L_{12\mu m}$ [10^{43} erg/s]	$L_{2-10keV}$ [10^{43} erg/s]	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0019-000	0.305	1521	220	GPS	0.472	2.441	G	—	—	3.53 ± 0.11	0.55 ^A	T09
0026+346	0.517	2852	190	GPS	0.743	2.491	Un	—	—	21 ± 0.3	23 ± 2	G06
0035+227	0.096	418	21.8	CSO	0.148	1.265	G	—	—	0.425 ± 0.007	0.075 ± 0.034	S16
0108+388	0.669	3907	22.7	CSO	0.132	3.159	G	9.86 ± 9.16	3.79 ± 1.40	<13.1	7 ± 3	T09,S16
0116+319	0.059	255	70.1	CSO	0.035	1.682	S*	0.595 ± 0.056	0.609 ± 0.046	0.629 ± 0.003	<0.10 [†]	S16
0402+379	0.055	234	7.3	CSO	0.099	1.721	G	0.48 ± 0.07	0.949 ± 0.059	0.608 ± 0.004	0.041 ± 0.016	R14
0428+205	0.219	1044	653	GPS	0.323	2.648	G	—	—	3.93 ± 0.08	1.4 ± 0.6	T09
0500+019	0.585	3319	55	GPS	1.047	2.892	G	63.4 ± 6.5	87.2 ± 9.8	59.3 ± 0.5	50 ± 6	T09
0710+439	0.518	2868	87.7	CSO	0.726	2.997	Sy	43.8 ± 4.4	107 ± 7	43.4 ± 0.4	39.40 ± 3.15	T09,S16
0941-080	0.228	1100	148	GPS	0.388	2.444	G*	—	—	2.57 ± 0.05	0.091 ± 0.075	T09
1031+567	0.460	2480	109	CSO	0.999	2.922	Q	17.6 ± 3.0	16.5 ± 4.7	15.6 ± 0.3	2.2 ± 0.2	T09,S16
1117+146	0.362	1874	306	GPS	0.406	3.599	SB	—	—	<5.87	1.40 ± 0.19	T09
1146+596	0.011	47	933°	CSO*	-0.011	1.237	G	0.0816 ± 0.0022	0.0818 ± 0.0033	0.1010 ± 0.0002	0.007	U05
1245+676	0.107	478	9.6	CSO	0.130	1.409	G	0.33 ± 0.14	0.358 ± 0.098	0.531 ± 0.006	0.031 ^{††}	W09,S16
1323+321	0.368	1908	247	GPS	0.303	2.014	G	—	—	2.54 ± 0.11	3.7 ± 0.4	T09
1345+125	0.122	551	166	CSO	1.308	3.930	Sy*	83.3 ± 1.7	216 ± 4	87.9 ± 0.2	7.8 ± 1.5	T09,J13
1358+624	0.431	2298	218	GPS	1.210	2.592	Q*	31.0 ± 2.4	37.8 ± 2.8	35.4 ± 0.2	30 ± 20	T09
1404+286	0.077	336	10.0	CSO	1.018	3.063	Q	50.9 ± 0.9	65.2 ± 1.3	51.6 ± 0.1	0.45 ± 0.06 ^C	T09,S16,S19b
1511+0518	0.084	370	7.3	CSO	1.233	2.899	Q	—	51.1 ± 3	52.2 ± 0.1	3 ^C	S16
1607+268	0.473	2569	240	CSO	0.287	2.679	S*	4.21 ± 3.17	21.6 ± 4.4	<7.27	3.79 ± 0.87	T09,S16
1718-649	0.014	60.4	2.0	CSO	0.136	2.462	G	0.322 ± 0.009	0.32 ± 0.01	0.401 ± 0.001	0.0154 ± 0.0024	S16
1843+356	0.763	4612	22.3	CSO	1.160	4.047	Sy	—	—	190 ± 1	5.60 ± 2.28	S16
1934-638	0.183	845	85.1	CSO	0.609	3.360	Sy*	5.89 ± 0.62	19 ± 1	6.52 ± 0.03	0.60 ± 0.14	S16,S19a
1943+546	0.263	1285	107.1	CSO	0.628	2.191	Un	—	—	5.64 ± 0.04	0.73 ± 0.28	S16
1946+708	0.101	444	39.4	CSO	0.663	2.336	Un	1.75 ± 0.15	1.67 ± 0.10	1.69 ± 0.01	1.20 ± 0.18	S16,S19a
2008-068	0.547	3056	218	CSO	0.334	2.159	G	—	7.68 ± 0.35	9.1 ± 0.4	6 ± 2	T09
2021+614	0.227	1086	16.1	CSO	1.287	3.009	Q	<210	—	64.9 ± 0.2	11.2 ^C	S16,S19a
2128+048	0.990	6364	218	GPS	0.688	3.352	Sy	—	63.9 ± 2.3	<52.4	29 ± 4	T09
2352+495	0.238	1143	117.3	CSO	0.688	2.714	Sy	—	—	4.25 ± 0.04	1.3 ± 0.3	T09,S16

Note. — **col(1)** — name of the source; **col(2)** — redshift; **col(3)** — luminosity distance; **col(4)** — linear size of the radio lobes taken from the references provided in col(13), ° except of 1146+596 cited from [Pettman et al. \(2001\)](#); **col(5)** — morphological/spectral radio classification: Compact Symmetric Object (CSO) based on the radio morphology, Gigahertz Peaked Spectrum (GPS) based on the spectral classification; classification follows the references given in col(13), * except of 1146+596 following from [Pettman et al. \(2001\)](#); **col(6)** — WISE Difference in the W1 (3.4 μm) and W2 (4.6 μm) color bands; **col(7)** — WISE Difference in the W2 (4.6 μm) and W3 (12 μm) color bands; **col(8)** — color classification: “Galaxy” (G), “Starburst” (SB), Quasar/Seyfert (Q/Sy), “Uncertain” (Un); possible contamination of WISE fluxes by background/foreground sources denoted by *; **col(9)** — IRAS 12 μm luminosity; **col(10)** — *Spitzer*/MIPS 24 μm luminosity; **col(11)** — WISE 12 μm luminosity calculated from the W3 band magnitude; **col(12)** — unabsorbed 2 – 10 keV luminosity taken from the references provided in col(13); ° extrapolated from the detection in the 0.5 – 2 keV band with photon index = 1.61; † estimated from the 0.5 – 2.0 keV upper limit < 0.5×10^{-14} erg cm $^{-2}$ s $^{-1}$ assuming photon index = 2.0; †† calculated based on the 4.5 – 12.0 keV PN flux; C value corresponding to the “Compton-thick” scenario; **col(13)** — X-ray references: [Guainazzi et al. \(2006\)](#) [G06], [Jia et al. \(2013\)](#) [J13], [Romani et al. \(2014\)](#) [R14], [Siemiginowska et al. \(2016\)](#) [S16], [Sobolewska et al. \(2019a\)](#) [S19a], [Tengstrand et al. \(2009\)](#) [T09], [Ueda et al. \(2005\)](#) [U05], [Watson et al. \(2009\)](#) [W09].

2.2 Sample Selection

As mentioned in Section 2.1 above, in this paper we consider only radio galaxies (i) for which the redshifts are measured, (ii) are characterized by compact radio structures with linear sizes $LS < 1$ kpc, and are classified morphologically as CSOs *and/or* spectrally as GPS sources, and (iii) that have available X-ray data. After a careful inspection of literature studies, we construct a “master sample” of such objects, the majority of which make up the samples discussed by [Tengstrand et al. \(2009\)](#) and [Siemiginowska et al. \(2016\)](#), with the addition of 0026+346, 0402+379, and 1146+596 (see [Guainazzi et al., 2006](#); [Willett et al., 2010](#); [Ostorero et al., 2017](#)). This amounts to a total of 29 targets, including 27 that have been detected in X-rays by either XMM-Newton or Chandra, one source with the X-ray flux measured by ASCA (1146+596; see [Ueda et al., 2005](#))¹, and one source having a Chandra upper limit for its 0.5 – 2.0 keV flux (0116+319; see [Siemiginowska et al., 2016](#)). Table 2.1 summarizes the basic information for the given sample, in particular, the 2 – 10 keV and MIR luminosities.

In the accompanying paper by [Wójtowicz et al. \(2020\)](#), we considered a smaller sample of the youngest X-ray detected radio galaxies, by imposing a much more restrictive selection criteria, namely (i) measured redshifts, (ii) strictly CSO morphological classification, in addition with *measured kinematic ages*, (iii) core X-ray fluxes measured with either XMM-Newton or Chandra. All of the 17 sources analyzed by [Wójtowicz et al.](#) are included in our master sample as well.

On the other hand, in our master sample we do not include X-ray detected compact radio galaxies lacking any robust GPS or CSO classification (e.g., 0046+316, 1146+531, 1217+295, 1231+481, 1254+571; see [Sobolewska et al., 2019b](#)), or classified before as GPS/CSOs but more recently re-classified as blazars (e.g., 1413+135; see [Willett et al., 2010](#)). We also do not discuss here the more evolved radio galaxies, classified morphologically as Medium Symmetric Objects (MSOs), and/or spectrally as Compact Steep Spectrum (CSS) sources (see [Kunert-Bajraszewska et al., 2014](#)). Finally, we do not include the Fanaroff-Riley type 0 (FR0) radio galaxies ([Głowacki et al., 2017](#); [Torresi et al., 2018](#)).

All in all, our master sample of the youngest radio galaxies, with available X-ray data, is composed predominantly (17/29) from the flux- and volume-limited set of targets extracted by [Tengstrand et al. \(2009\)](#) and [Guainazzi et al. \(2006\)](#), from a complete sample of GPS sources compiled by [Stanghellini et al. \(1998\)](#), by applying cuts on redshift, $z < 1$, and the 5 GHz flux density, $F_{5\text{ GHz}} > 1$ Jy. For this sub-sample, the X-ray detection rate is particularly high, namely 100% (including 0019-000 which has been detected with XMM-Newton only in the soft 0.5–2.0 keV band). Secondly, our master sample includes a set (10/29) of CSOs at $z < 1$, *with available kinematic age measurements*, selected for Chandra study by [Siemiginowska et al. \(2016\)](#). These sources are not flux or volume limited, and the radio luminosities are on average lower than that

¹The analysis of the archival and previously unpublished Chandra data for 1146+596 will be presented in a forthcoming paper.

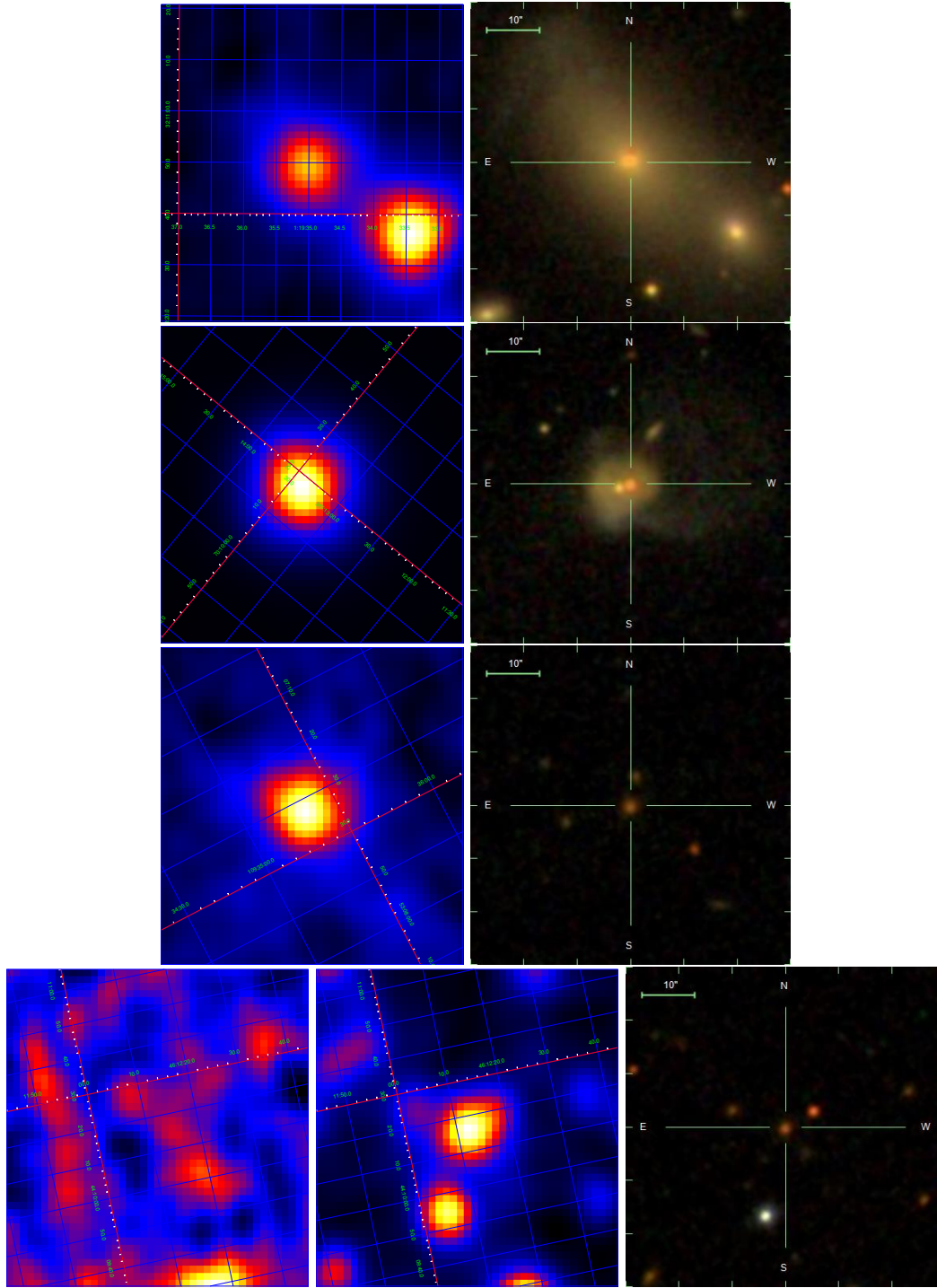


Figure 2.1: *WISE* $12\,\mu\text{m}$ images with overlaid ecliptic coordinate grids (left panels), along with the SDSS gri color composite images (right panels) for 0116 + 319, 1345 + 125, 1358 + 642, and 1607 + 268 (rows from top to bottom). In the case of 1607 + 268 (bottom row), the *WISE* $3.4\,\mu\text{m}$ image is presented in addition (central panel). Images are equal in size, being a square $60''$.

of the [Tengstrand et al. \(2009\)](#) sub-sample; still, all but one (0116+319) of the sources selected by [Siemiginowska et al. \(2016\)](#) have been detected with *Chandra*, despite short exposures, ~ 5 ksec, for the majority of the targets. In addition to the sources in the above-mentioned sub-samples, we have also included two particularly compact and nearby CSOs, namely 0402+379 (see [Willett et al., 2010](#)), and 1146+596 (see [Ostorero et al., 2017](#)), in our master list.

2.3 MIR Data Acquisition

2.3.1 MIR Data

In this study we utilize three infrared telescopes: the Wide-field Infrared Survey Explorer (*WISE*), the Infrared Astronomical Satellite (*IRAS*), and the *Spitzer* instrument, the Multiband Imaging Photometer (*MIPS*) for NASA’s Space Infrared Telescope Facility (*SIRTF*). Each instrument has differing operating capabilities, all of which are detailed below.

WISE is an all sky survey mission covering the entirety of the northern and southern sky. The telescope obtains measurements in four bands (W1–W4) centered at 3.4, 4.6, 12, and 22 μm respectively. The resolution in each of the bands is as follows: 6.1'', 6.4'', 6.5'', & 12'' in each of the four bands (W1, W2, W3, W4; [Wright et al., 2010](#)). *IRAS* surveys the sky at slightly longer wavelengths than *WISE*; its bands are centered at 12, 25, 60 and 100 μm . We utilize the 12 μm measurements for this work with a resolution of 0.5', notably larger than *WISE*. It is prudent to note that the *IRAS* 12 μm band has a width of 6.5 μm , whereas the *WISE* 12 μm has a band width of 5.5 μm . This results in the *IRAS* measurements being on average slightly higher than the *WISE* measurements. *MIPS* images the sky with bands centered at: 24, 70, and 160 μm . For this work we inspect the 24 μm measurements with a given resolution of 6'', comparable to *WISE*.

2.3.2 Source Contamination

Due to the angular resolution of *WISE*, and the significantly lower resolution of the *IRAS* instrument, source contamination due to galaxies in close proximity to our sources is possible. In order to diagnose any potential contamination, visual inspection of optical and infrared images of all sources in our sample was performed to assess if any contaminating objects lie within the field of view of the *WISE* or *IRAS* instruments. This inspection was paired with a literary search using the NASA/IPAC Extragalactic Database (NED) to identify the classification of any objects within 12'' of our sources. For this search, we restrict our inspection to only galaxies and stellar objects as their infrared luminosities are significant enough to cause a detectable shift in the infrared measurements of our sources. We note that we do not consider any unresolved infrared sources as contaminating objects.

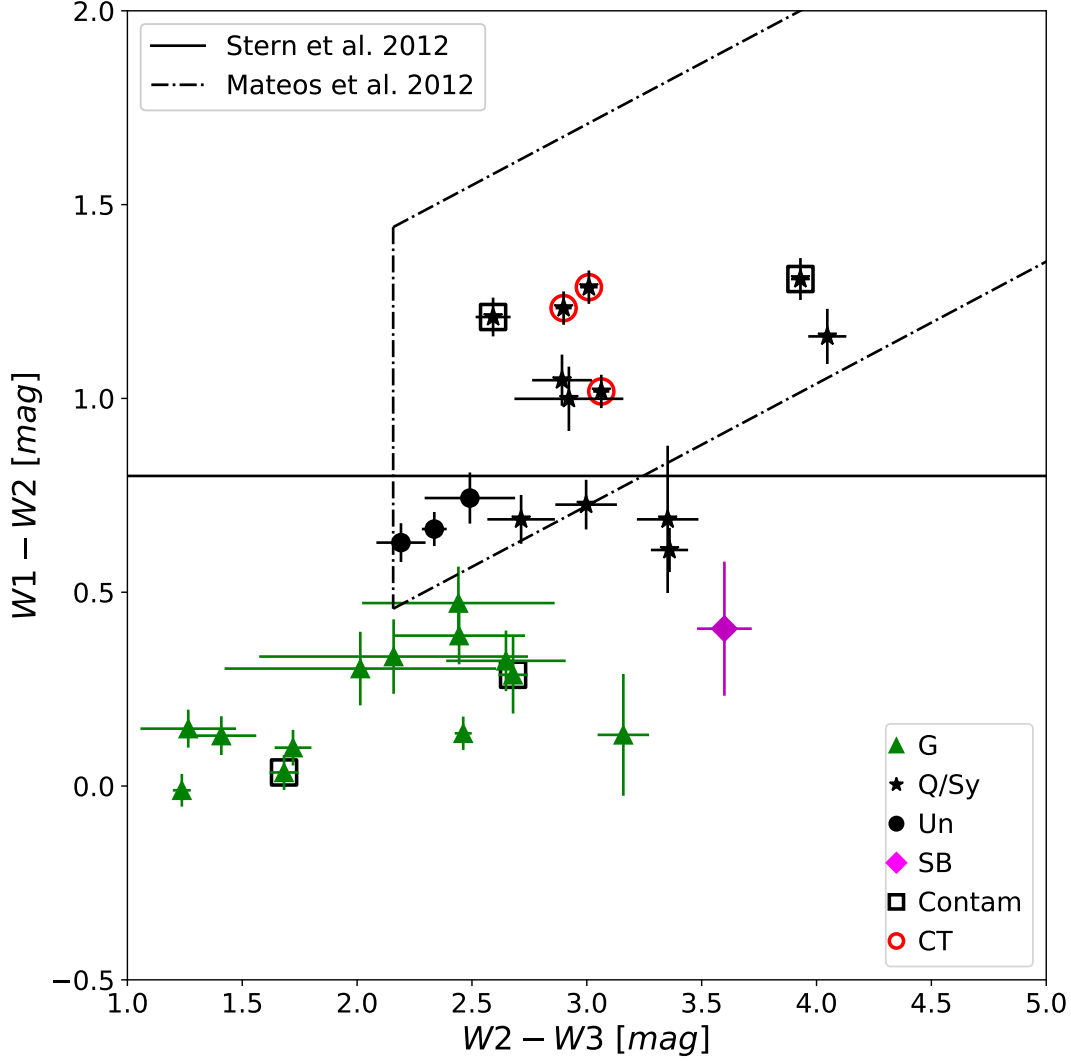


Figure 2.2: *WISE* color-color diagram for compact radio galaxies included in our sample. Different symbols denote *WISE* color classification following [Wright et al. \(2010\)](#): “Galaxy” (G) – green triangle, “Starburst” (SB) – purple side-pointing triangle, “Quasar/Seyfert” (Q/Sy) – black star, “Uncertain” (Un) – black circle; sources marked with a black square may have a significant contamination from nearby background/foreground objects; red circles indicate objects confirmed as Compton-thick based on the X-ray spectroscopy. The horizontal solid line delineates the [Stern et al. \(2012\)](#) cut: the MIR emission of sources located above the line is dominated by an AGN component. The dotted, dashed lines show the [Mateos et al. \(2012\)](#) cut: the MIR emission of sources located within wedge is dominated by an AGN component.

In addition to the known interacting binary systems, 0941 – 080 and 1934 – 638, discussed in [de Vries et al. \(1998\)](#) and [Jauncey et al. \(1986\)](#) respectively, we conclude that contamination in the *WISE* bands is possible in 8 of the 29 sources in our sample. Out of these, the following sources are expected to only have contamination in the longest-wavelength *WISE* band, W4 (resolution of $12''$), which we do not use for our color classification or in further analysis: 0019 – 000, 1031 + 567, 1117 + 146 and 1323 + 321. Therefore, for these four sources, the *WISE* color classification is expected to be unaffected by the nearby galaxies/stars, however, there is a potential for mild contamination in their *IRAS* fluxes. We note that from these only 1031 + 567 has available *IRAS* flux measurements, and the difference in the measured flux between the *IRAS* and *WISE* is 12%, see Table 2.1.

Contamination in the *WISE* color classification for the following sources is likely: 0116 + 319, 1345 + 125, 1358 + 624, and 1607 + 268, all marked in Table 2.1. These sources have galaxies and/or stars closer than $6.5''$, and as such would contain some level of excess flux in all four *WISE* bands and result in a shift in the positioning on our diagnostic plot. These four cases can be viewed in Figure 2.1, which displays the *WISE* $12\mu\text{m}$ image and the respective Sloan Digital Sky Survey (SDSS) color composite image of each source. Optical images are color composite images of the $g(4770\text{ \AA})$, $r(6231\text{ \AA})$, and $i(7625\text{ \AA})$ bands obtained through the SDSS sky server. It can be clearly seen that the *WISE* images show a blending or merging of nearby objects that in the SDSS image are more clearly seen as separate objects. For the specific case of 1607 + 268 which has a very low flux in the $12\mu\text{m}$ band; we provide the $3.4\mu\text{m}$ band image as well. The morphology of 1345 + 125 is discussed in detail in [Axon et al. \(2000\)](#).

We finally note one source in particular, 2021 + 614, which shows a significant difference between the *IRAS* and *WISE* flux measurements. The calculated *IRAS* luminosity is 223% higher than the respective *WISE* luminosity. This is most likely due to unresolved infrared sources near to 2021 + 614 as well as poor data quality provided by *IRAS*. We comment, however, that the difference in the fluxes provides little change to our conclusions.

2.3.3 MIR Photometry

The *WISE* colors, W1–W2 and W2–W3, can be utilized to diagnose the suggested level of star formation within a source and suggest the type of source being observed. The *WISE* colors for all sources in our sample have been estimated in a standard manner based on photometry in the W1 ($3.4\mu\text{m}$), W2 ($4.6\mu\text{m}$), and W3 ($12\mu\text{m}$) bands. The W1–W2 and W2–W3 color values are provided in Table 2.1, and plotted in Figure 2.2. Based on those colors, and following the diagnostic plot provided in [Wright et al. \(2010\)](#), we have grouped our sources into distinct types denoted as “Galaxy” (G), “Starburst” (SB), Quasar/Seyfert (Q/Sy), or — if the color falls in a non-defined region of the diagnostic plot — “Uncertain” (Un). G type sources encompass the region of the plot associated with star formation levels typical of Elliptical and Spiral morphology.

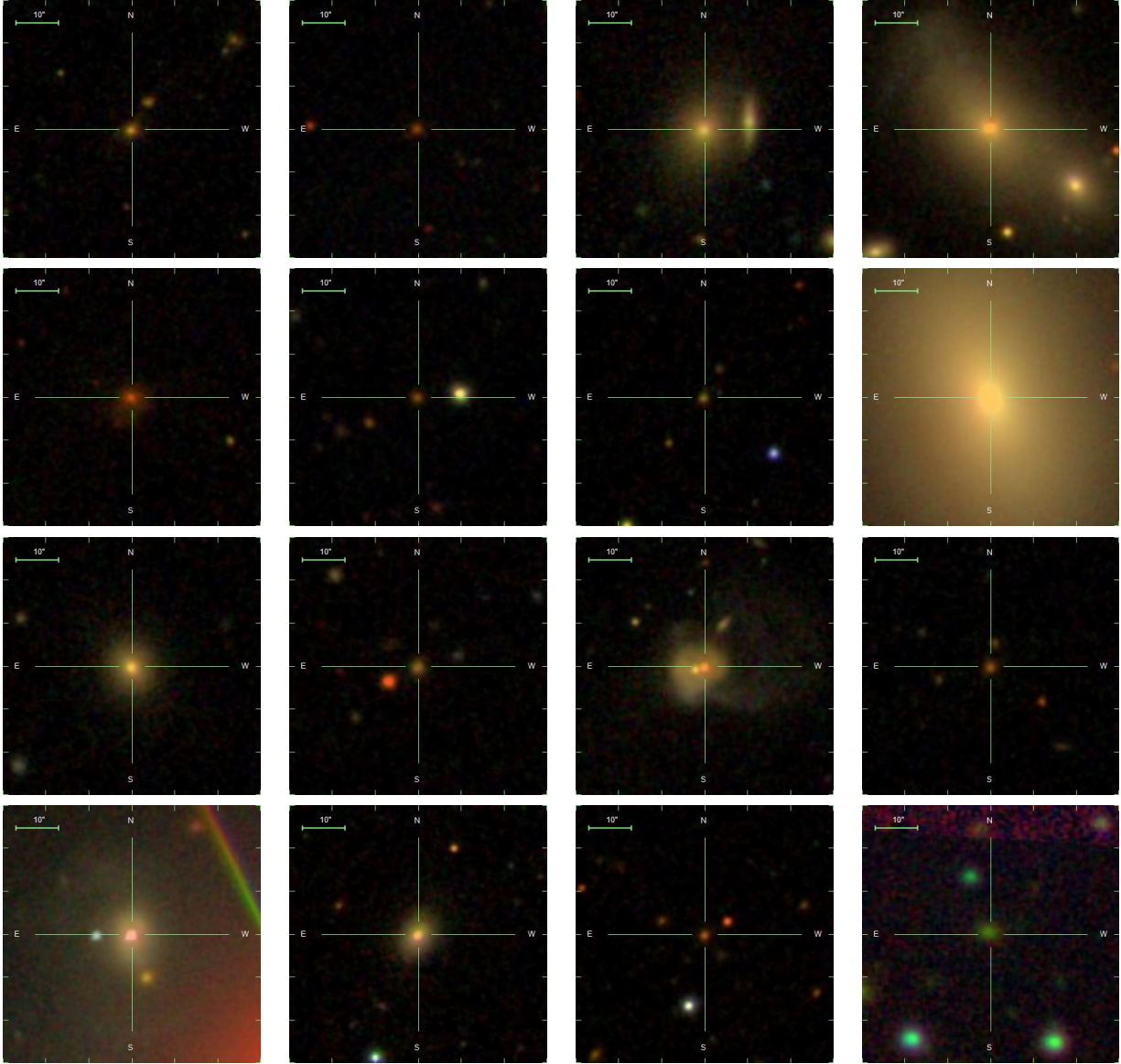


Figure 2.3: The SDSS gri color composite images of the host galaxies, available for 17 sources from our list ([Abolfathi et al., 2018](#)), excluding the particularly faint 2128+048; these are (from left to right) 0019–000, 0026+346, 0035+227, 0116+319 (first row), 0428+205, 1031+567, 1117+146, 1146+596 (second row), 1245+676, 1323+321, 1345+125, 1358+624 (third row), 1404+28, 1511+0518, 1607+268, 2352+495 (fourth row). In each image, the position of the source is indicated by a cross, while the image scale is shown in the upper left corner, with each image being a square 60''.

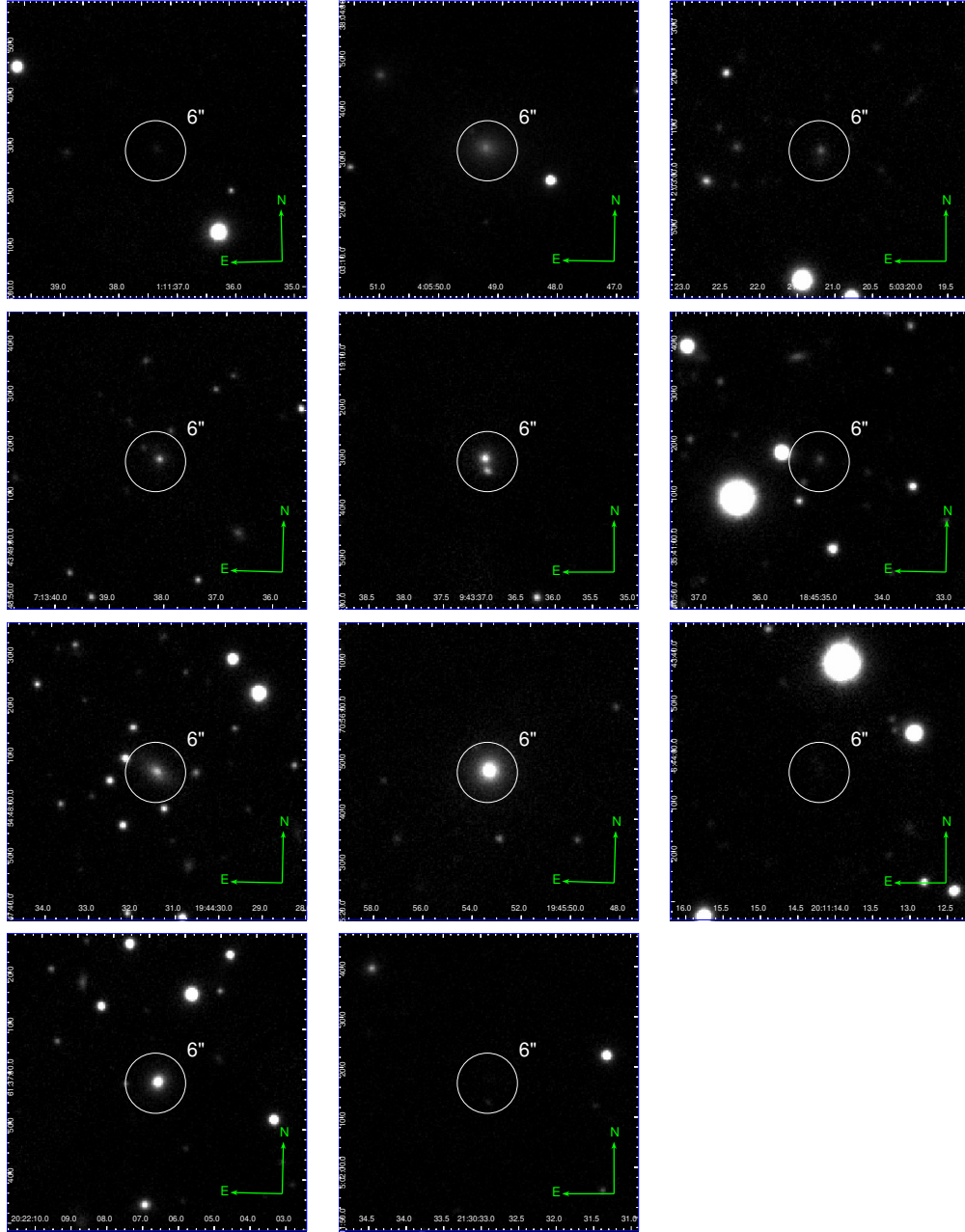


Figure 2.4: Optical images of sources not covered by SDSS (or too faint for SDSS), but observed instead by the all sky survey PanSTARRS, in the i band ($7563 \text{ \AA}$), including (from left to right) 0108+388, 0402+379, 0500+019 (first row), 0710+439, 0941–080, 1843+356 (second row), 1943+546, 1946+708, 2008–068 (third row), 2021+614, and 2128+048 (fourth row). In each image with overlaid ecliptic coordinate grids, the position of the source is indicated by a circle with a diameter of $6''$ with each image being a square $60''$.

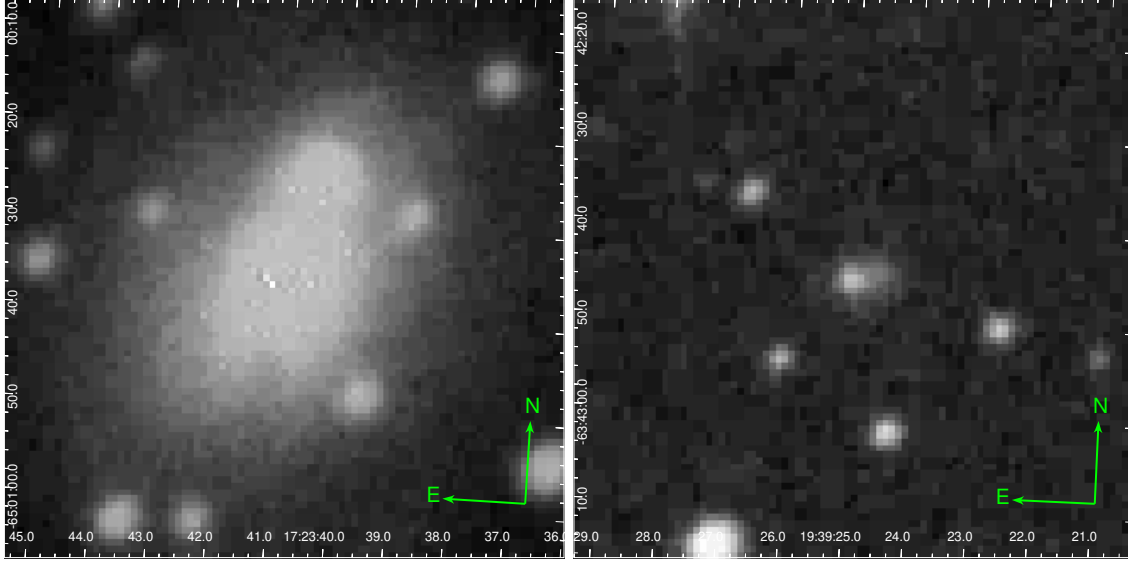


Figure 2.5: Additional optical images in the UKST blue band of the two southernmost sources 1718–649 (left panel) and 1934–638 (right panel), obtained from the Super Cosmos Sky Surveys. In each image, the position of the source is in the center of the image with each image being a square $60''$ and containing overlaid ecliptic coordinate grids.

Infrared magnitudes were obtained for all 29 sources from *WISE*, and their luminosities were calculated using standard flux relations. In addition, $12\ \mu\text{m}$ were obtained from *IRAS* measurements for 16 out of the 29 sources, with the corresponding luminosities provided in Table 2.1. We provide the $12\ \mu\text{m}$ *IRAS* and $24\ \mu\text{m}$ *MIPS* luminosities for comparison with the obtained *WISE* values. We note that all but four sources have comparable $24\ \mu\text{m}$ *MIPS* luminosities to the $12\ \mu\text{m}$ *WISE* and *IRAS* measurements. 0710+439, 1345+125, 1607+268, and 1934-638 show an increase of 140 – 210% in the $24\ \mu\text{m}$ band, are all classified as Sy, and are all morphologically classified as CSO. We note these four sources for further investigation in a follow-up paper, as potentially interesting sources to inspect spectroscopically.

2.4 Results & Discussion

2.4.1 *WISE* Colors and Host Galaxy Morphologies

Figure 2.2 presents the *WISE* color diagnostic plot, with different symbols reflecting the *WISE* color identification following Wright et al. (2010). Clearly, such an identification does not serve as a rigorous classification, as it only points out the most likely origin of the detected MIR fluxes, corresponding to either the ISM with various levels of the star formation activity (G, SB) or the

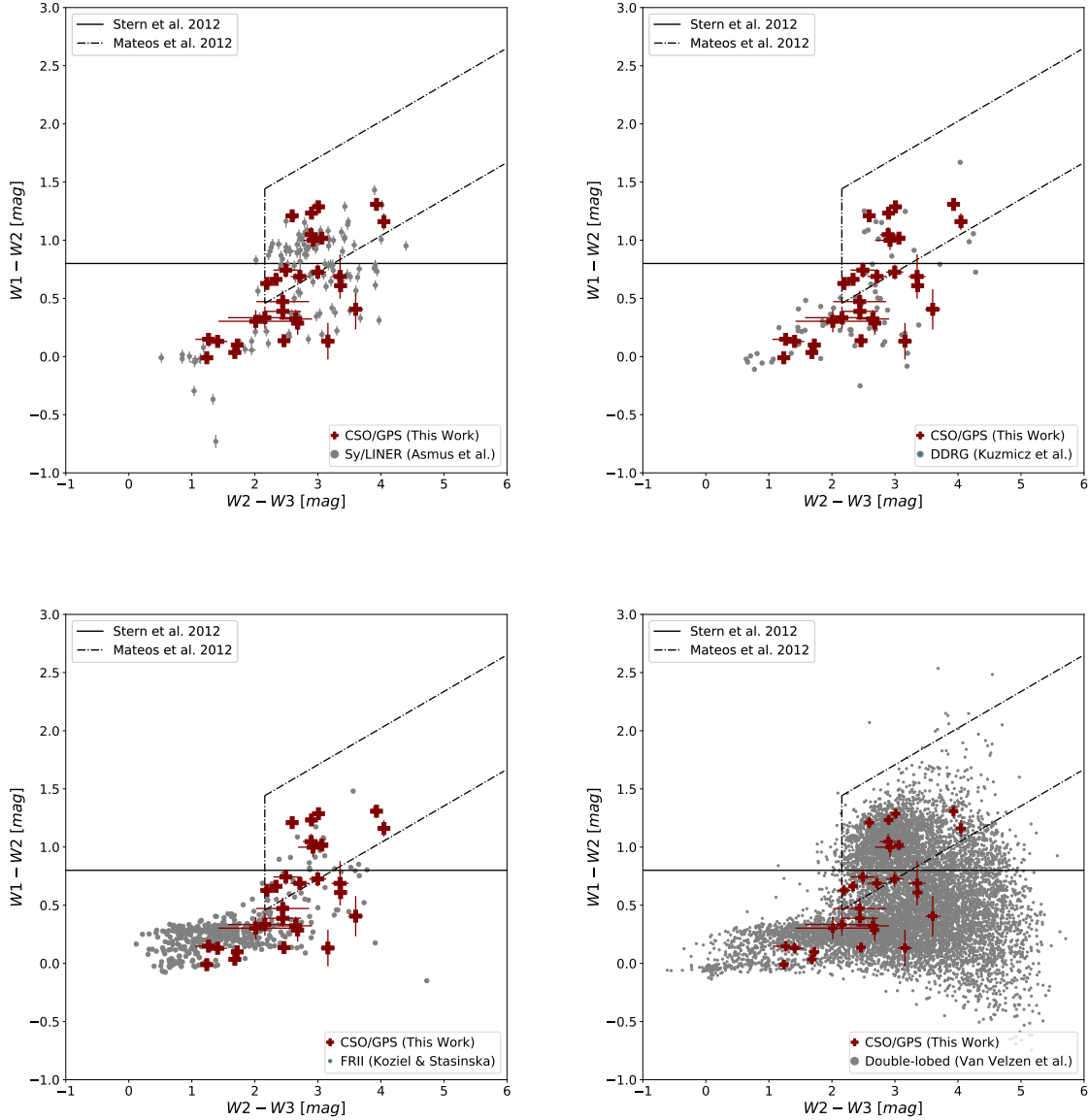


Figure 2.6: Top left panel: A comparison of the [Asmus et al. \(2014\)](#) AGN sample of local Seyferts and LINERs with our sample of 29 GPS/CSO sources. Top right panel: A comparison of the [Kuźmicz et al. \(2017\)](#) sample of restarted radio galaxies (DDRGs) with our sample of 29 GPS/CSO sources. Bottom left panel: A comparison of the [Kozieł-Wierzbowska & Stasińska \(2011\)](#) sample of evolved classical doubles (FR II-type radio galaxies), with our sample of 29 GPS/CSO sources. Bottom panel: A comparison of the [van Velzen et al. \(2015\)](#) double-lobed radio sources sample with our sample of 29 GPS/CSO sources. The displayed cuts in all panels are the same as in Figure 2.2. Larger red crosses in each panel indicate the objects in our sample with small grey circles in each plot denoting the respective comparison sample.

AGN component (Q/Sy).² Quasar and Seyfert like galaxies are collected into one group due to significant overlap of their individual regions in the color–color diagram, however, we differentiate these sources in Table 2.1. This identification is, on the other hand, consistent with the selection cut introduced by Stern et al. (2012), and represented in the figure by a solid horizontal line: all the young radio galaxies with the *WISE* colors of the Q/Sy type, are indeed located either very close to the line, or much above it, and this substantiates the dominant AGN (dusty torus) contribution to the MIR emission in their cases. The overwhelming majority of our sources with the *WISE* classifications of Q/Sy, as well as all classified as Uncertain, fall within the Mateos et al. (2012) cut, which constitutes a reliable MIR color selection of luminous AGN, constructed based on the flux-limited wide-angle Bright Ultrahard XMM-Newton Survey (BUXS; 4.5 – 10 keV flux limit of $6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$).

Let us comment here on a few cases from our sample with “uncertain” *WISE* color identification. These sources lie, in fact, within the so-called “blazar strip” (Massaro et al., 2012), which may suggest that their MIR fluxes are dominated by a non-thermal jet-related emission. Unlike in blazar sources, however, such an emission does not have to be relativistically beamed, but instead may constitute a high-energy tail of the synchrotron continuum of compact radio lobes expanding with sub-relativistic ($\lesssim 0.1c$) velocities (see in this context the broad-band modelling by Ostorero et al., 2010).

Interestingly enough, all the objects in the sample confirmed as Compton-thick, based on the X-ray spectroscopy (1404+286, 1511+0518 and 2021+614; see Siemiginowska et al., 2016; Sobolewska et al., 2019b,a, respectively), are characterized by the *WISE* colors as being consistent with a quasar identification, as in fact expected. Hence, *WISE* color diagnostics could, in general, be considered as a very useful tool when selecting candidates for Compton-thick AGN among compact radio galaxies.

²Note in this context the overlaps between different types of galaxies in the *WISE* color classification: for example 1345+125, denoted here as “Sy”, can additionally be classified as Ultraluminous Infrared Galaxy (ULIRG; e.g., Rodríguez Zaurín et al., 2009).

Table 2.2. *WISE* 2D KS Test Results

Sample Set	p -value	D value
Asmus et al.	0.0795	0.282
Koziel & Stasinska	0.95×10^{-7}	0.60
Kuzmicz et al.	0.065	0.31
Van Velzen et al.	0.0028	0.37

CHAPTER 2. MIR DIAGNOSTICS OF YOUNG RADIO GALAXIES

The most striking feature of the diagram is, however, the fact that the most compact radio galaxies with colors $W1-W2 \leq 0.5$ mag, i.e. those presumably dominated in MIR by the ISM radiative output, populate almost uniformly the entire region occupied by galaxies (from elliptical to starbursts) with the $W2-W3$ colors between 1.0 and 4.0, suggesting a wide range of pronounced star formation activity within their hosts. Such a diversity could imply that the triggering of radio jets in AGN is not differentiated between hosts with substantially different fractions of young stars.

In this context, we investigate the optical images of the host galaxies in our sample. SDSS images of the host galaxies (Abolfathi et al., 2018) are available for 17 sources from our list; these are shown in Figure 2.3 (excluding the particularly faint 2128+048). In each image, the position of the source is indicated by a cross, while the image scale is shown in the upper left corner. These images are combined color images of the u, g, r, i, and z optical bands, obtained through the SDSS DR15 Navigate Tool. The SDSS images of the majority of our galaxies allow for an approximate morphological classification (the only exceptions are 2128+048, which is too faint to be classified, and 2352+495, whose image shows false colors).

Most of the sources are red/yellow galaxies with an elliptical shape. Five galaxies have distorted morphology or show the signs of galaxy interaction; these are 0035+227, 0116+319, 0428+205, 1345+125, and 1404+286. None of the galaxies classified as “galaxy” in the MIR color diagram shows the indication of a spiral structure. On this basis, we can conclude that the MIR colors differentiate galaxies with different levels of star formation, but they are loosely related to morphological types.

For the remaining sources which are not covered by the SDSS, or which are too faint for the SDSS, we retrieved the optical images of the hosts from the all sky survey PanSTARRS (Chambers et al., 2016), in the i band (7563 Å), and, in the case of the two southernmost objects 1718-649 and 1934-638, from the Super Cosmos Sky Surveys in the UKST blue band; these are shown in Figures 2.4 and 2.5, respectively. Again, most of those galaxies whenever bright enough to be classified morphologically, display elliptical shapes, with the exception of the peculiar 1718-649 host, “*having the appearance of a high luminosity elliptical with faint outer spiral structure*” as noted by Fanti et al. (2000). We comment more on this object in Section 2.4.3. These images are shown as strictly optical intensity and as such no comments on their colors are made. We note that 0108+388, 2008-068, and 2128+048 are too faint in optical for any classification.

It is interesting to compare the distribution of the *WISE* colors in our sample of young radio galaxies with comparison samples of various types of active galaxies. For this purpose, we consider first the list of local (redshifts $z < 0.4$) AGN compiled by Asmus et al. (2014), which includes 102 sources selected from the nine months of observations with the Burst Alert Telescope (BAT) onboard the *Swift* satellite within the 14 – 195 keV band (constituting a flux limited sub-sample in the list), complemented by the AGN with the available high-resolution MIR imaging enabled by ground-based 8m class telescopes such as VLT/VISIR, Gemini/Michelle, Subaru/COMICS, or Gemini South/T-ReCS. All together there are 253 sources in the Asmus et al. sample, for which the optical spectroscopic classification includes Seyferts type I, Seyferts type II, LINERs, and

AGN/starburst composites. Moreover, the AGN from this sample are hosted by various types of galaxies, including late type galaxies with bona-fide spiral structures, not only elliptical or disk systems.

The distribution of the *WISE* colors for the [Asmus et al. \(2014\)](#) sample, in a direct comparison with our sample of GPS/CSOs, is shown in the top left panel of Figure 2.6. In order to establish a secure sample of *WISE* sources, we performed two quality cuts to remove any uncertain measurements. First we removed all sources that had a null or < 1 signal to noise ratios (snr) for bands W1, W2, & W3. Following this cut, we removed any sources with flagged contamination (marked by *cc_flags* not equal to 0). These cuts left us with a sample of 121 sources from the original 253 sources in the [Asmus et al.](#) sample. Both distributions appear very similar and we quantify this statement by performing the two-dimensional Kolmogorov-Smirnov (2D KS) test, that was developed through the efforts to generalize the classical one-dimensional KS test to two ([Peacock, 1983](#)) and higher dimensions ([Fasano & Franceschini, 1987](#)). In particular, we follow the 2D KS algorithm described in [Fasano & Franceschini \(1987\)](#) and calculate — under the null hypothesis that the two analyzed samples were drawn from the same distribution — the two-tailed *p*-value (i.e., the probability of obtaining a value of the statistic *D* greater than the observed value, if the null-hypothesis were true). As a result, we obtain $p = 0.0795$ and $D = 0.282$; adopting a significance level of $\alpha = 0.05$, this result implies that the null hypothesis should be accepted.

We note that the [Asmus et al. \(2014\)](#) sample includes both radio-quiet and also radio-loud objects — either low-power radio galaxies of the Fanaroff-Riley type I (FR Is), or high-power classical doubles, i.e. Fanaroff-Riley type II radio galaxies (FR IIs) — however, the radio properties were not taken into account when selecting the sample. That is, neither a detection of a radio counterpart nor a particular threshold value for the radio loudness parameter constituted a selection criterion. It is therefore interesting that the distribution of the *WISE* colors for this “hard X-ray selected/quasi MIR selected” sample of local AGN with the median redshift $z = 0.016$, is statistically similar to the distribution of *WISE* colors in our sample of the youngest radio galaxies, selected based on their radio properties and availability of X-ray data, and in addition spanning a wider range of redshifts from 0.011 up to 0.99, with the median of $z = 0.238$. We note, however, that we are looking at a smaller set of the [Asmus et al. \(2014\)](#) sample, due to the quality cuts necessary for the *WISE* data, which could impose some unexpected selection effects.

Second, we compare the MIR colors of our GPS/CSOs with those characterizing the *evolved* (extended) FR II type radio galaxies. In particular, we consider the FR II sample by [Kozieł-Wierzbowska & Stasińska \(2011\)](#), which resulted from cross-identification of the objects included in the Cambridge Catalogues of Radio Sources (3C–9C) with galaxies from the SDSS DR7 main galaxy sample, after excluding quasars and only keeping the objects with clear FR II large-scale radio morphology, investigated manually based on the available radio maps from the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-cm (FIRST) survey. This sample amounts to 401 sources spanning a redshift range from 0.045 up to 0.6, which is well matched to the redshift range in our GPS/CSO sample.

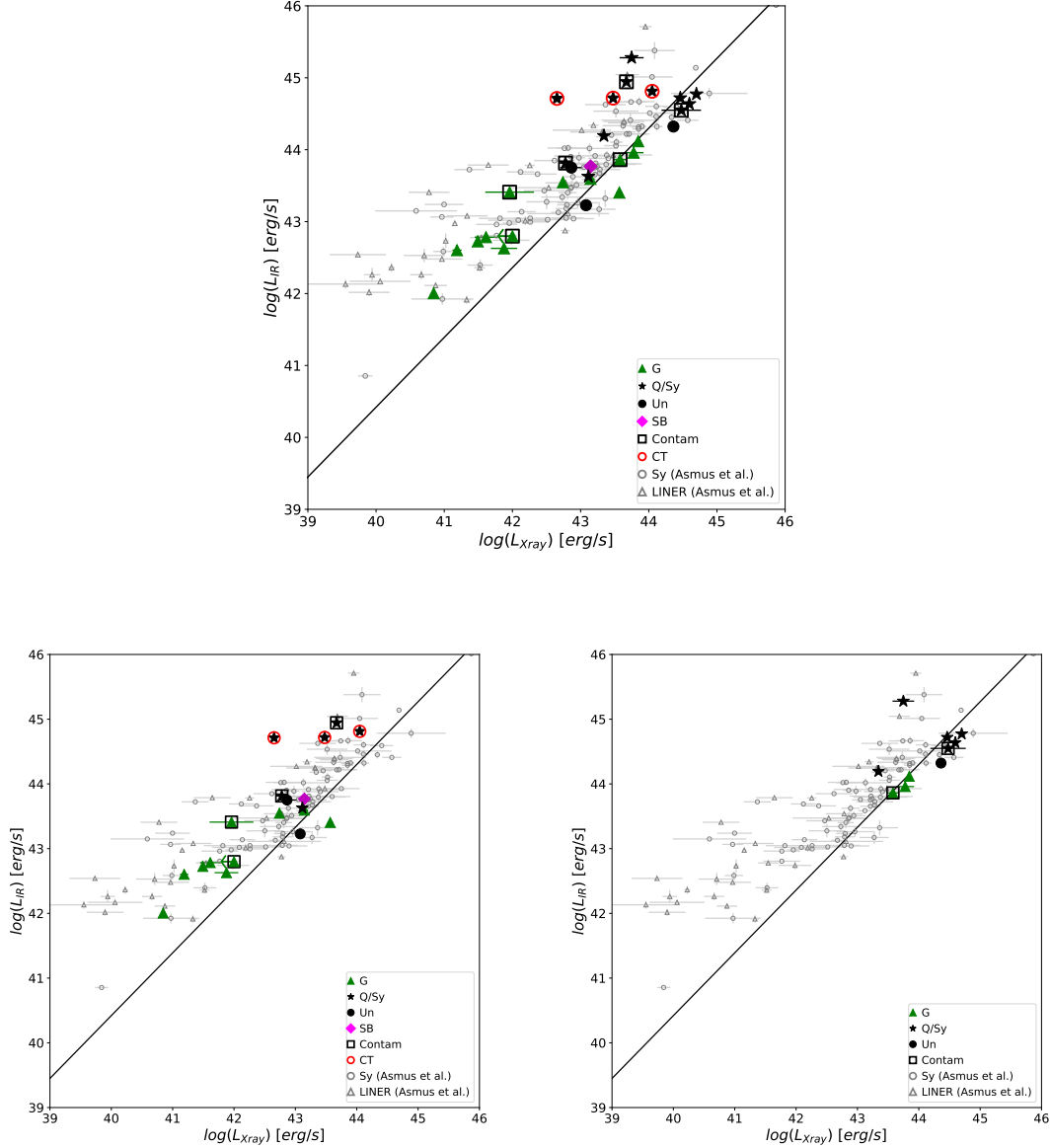


Figure 2.7: Relation of the *WISE* $12\,\mu\text{m}$ and the intrinsic (absorption-corrected) 2–10 keV luminosities for our compact radio galaxies denoted by large symbols (symbols and colors are the same as in Figure 2.2). Source 0116 + 319 has an upper limit X-ray luminosity and is marked with a left pointing arrow, visible on the lower left end of the plot. The solid line shows the correlation established for nearby AGN by Asmus et al. (2015) based on the high-angular resolution MIR (ground-based) observations; small grey symbols denote the AGN from the Asmus et al. (2014) sample with *IRAS* $12\,\mu\text{m}$ luminosities. In the upper panel we show the entire GPS/CSOs sample, in the lower-left panel only the young radio galaxies with $z < 0.4$, and in the lower-right panel only those with $z > 0.4$.

The distribution of the *WISE* colors for the [Kozieł-Wierzbowska & Stasińska \(2011\)](#) sample, in a direct comparison with our sample of GPS/CSOs, is presented in the top right panel of Figure 2.6. As shown, the analyzed GPS/CSOs, as a population, have significantly different MIR colors than FR IIs. Unlike compact radio galaxies, the evolved FR IIs typically cluster within the area of the color diagram occupied by elliptical galaxies with very little star formation activity. In addition, we note that the sample selection adopted by [Kozieł-Wierzbowska & Stasińska \(2011\)](#), specifically the removal of SDSS classified quasars, may result in a reduction of bright AGN in this sample. Again, we quantify our statement by running the 2D KS test, and obtain $D = 0.6$ with the corresponding $p = 0.95 \times 10^{-7}$, meaning that the null hypothesis stating that the two samples were drawn from the same distribution, can be safely rejected at the adopted significance level, $\alpha = 0.5$. This result is in fact unexpected, as CSOs (at least the most luminous ones) are widely considered to be a young progenitor of FR II radio galaxies (see, e.g., [Perucho, 2016](#), and references therein), and the evolution of radio structures from a compact (< 1 kpc) CSO phase to an evolved (linear sizes ~ 10 s– 100 s kpc) classical double phase, takes only up to ~ 100 Myr, which is much shorter than the timescale required for host galaxy evolution from a late to an early type.

Third, we consider the sample of radio galaxies with confirmed recurrent jet activity, i.e. radio galaxies displaying clearly extended/outer radio lobes (predominantly of the FR II morphological type), in addition to a compact/inner double structure produced during the distinct, newborn jet phase. For these so-called “double-double radio galaxies” (DDRGs; see [Schoenmakers et al., 2000](#)), we use the list recently compiled by [Kuźmicz et al. \(2017\)](#), including 73 sources within a redshift range $0.002 < z < 0.7$. The distribution of the *WISE* colors for this sample is given in the bottom left panel of Figure 2.6. The 2D KS test in this case returns $D = 0.31$ with the corresponding $p = 0.065$, meaning that at the significance level of $\alpha = 0.05$, the *WISE* colors for both samples of DDRGs and GPS/CSOs considered here, were drawn from the same distribution.

Finally, we inspect the *WISE* color distribution of our sample of GPS/CSOs against a larger sample of double-lobed radio sources, compiled by [van Velzen et al. \(2015\)](#) by means of an automated search algorithm applied to the FIRST survey. With the adopted five quality cuts — optimized with respect to the angular size of the respective systems, their radio fluxes, as well as their radio core prominence — the sample of [van Velzen et al.](#) consists of 24,973 sources that

Table 2.3. IR–Xray 2D KS Test Results

Sample Set	p -value	D value
Full Sample	0.10	0.26
$z < 0.4$	0.25	0.26
$z > 0.4$	1.8×10^{-4}	0.7

could be safely considered as representing FR II-type radio galaxies, with radio fluxes extending down to the adopted 12 mJy limit. We performed the same two quality cuts to remove any uncertain measurements as the [Asmus et al.](#) sample. We removed all sources that had a null or < 1 signal to noise ratios (snr) for bands W1, W2, & W3 as well as all sources with *c_flags* not equal to 0. These cuts left us with a sample of 9,740 sources from the original 24,973 sources in the [van Velzen et al.](#) sample. The distribution of the *WISE* colors for this sample is given in the bottom right panel of Figure 2.6. The 2D KS for this and our sample returns a value of $D = 0.37$ with the corresponding $p = 0.0028$, signifying that the two data sets were not drawn from the same distribution. Indeed, it is apparent that one of the main differences here is the lack of GPS/CSOs within the region of the *WISE* color diagram occupied by galaxies forming stars at very high rates (starbursts, luminous- and ultraluminous-infrared galaxies), where, in contrast, many double-lobed FIRST radio sources can be found. This could signify that, either the youngest radio sources avoid hosts with very vigorous starformation, *or* that we are dealing with an observational bias that does not allow for differentiation of compact jets and lobes (and therefore for the “GPS/CSO” classification) in the presence of a strong radio emission from the central starburst region.

The results from all *WISE* color 2D KS tests are summarized in Table 2.2.

2.4.2 MIR/X-ray Correlation

A similarity in the MIR colors between our GPS/CSOs and the general population of bright local AGN, prompted us to investigate a correlation between MIR and X-ray luminosities in young radio galaxies. The relationship between MIR and X-ray luminosities in various samples of AGN and in different photon energy ranges have been studied extensively in recent years. Different infrared instruments have been utilized in such analysis, including the low-resolution ISO ([Lutz et al., 2004](#); [Ramos Almeida et al., 2007](#)), *Spitzer* ([Hardcastle et al., 2009](#); [Sazonov et al., 2012](#)), AKARI ([Matsuta et al., 2012](#); [Ichikawa et al., 2012](#)), and *WISE* ([Mateos et al., 2015](#); [Stern, 2015](#)) instruments. Studies with high-resolution ground-based telescopes turned out particularly conclusive in this context, as they disclosed a tight correlation between the *nuclear* MIR luminosities and the 2–10 keV luminosities of the targeted AGN, which has important implications for understanding the structure of circumnuclear dusty tori in active galaxies in general (see, e.g., [Horst et al., 2008](#); [Levenson et al., 2009](#); [Gandhi et al., 2009](#); [Asmus et al., 2011, 2015](#)).

In the upper panel of Figure 2.7 we plot the *IRAS* 12 μm and the intrinsic (absorption-corrected) 2–10 keV luminosities for the entire sample of our compact radio galaxies (see Table 2.1; large symbols in the figure), along with the comparison AGN sample by [Asmus et al. \(2014\)](#) introduced in the previous section, for which the 12 μm luminosities were obtained similarly with the *IRAS* satellite (small grey symbols). In the cases of our sources we utilize the *WISE* 12 μm measurements; note the $\sim 6.5''$ *WISE* resolution at 12 μm compared to the *IRAS* angular resolution of $\sim 30''$ at 12 μm . The differences in angular resolution of the instruments can result in the *WISE* measurements viewing a smaller region of the targeted source. Still, even with such, we are not able to extract

solely the innermost nuclear regions of the galaxies, and so all of the sources included in the figure are expected to have a significant contribution from the ISM component in their MIR luminosities, this is in addition to the circumnuclear dust emission (if present). In this context, the solid line in Figure 2.7 denotes the best-fit linear relation between the logarithms of the luminosities, obtained by Asmus et al. (2015) when using the *high-resolution* MIR observations with ground-based telescopes, for their (Asmus et al., 2014) Seyfert+LINER sample,

$$\log\left(\frac{L_{12\mu\text{m}}}{10^{43} \text{ erg s}^{-1}}\right) = 0.33 + 0.97 \log\left(\frac{L_{2-10\text{keV}}}{10^{43} \text{ erg s}^{-1}}\right). \quad (2.1)$$

As evident from the figure, the AGN from the comparison sample are located mostly above the best-fit correlation line, as expected keeping in mind the relatively poor angular resolution of *IRAS*, and the fact that the best-fit correlation was established based on sub-arcsec MIR photometry, and so without any significant ISM emission component. Note that the relative contribution of the ISM to the total MIR flux detected with *IRAS* increases for low-luminosity AGN (LINER), as expected.

The distribution of young radio galaxies in the diagram, at the first glance, resembles the distribution of the comparison local AGN sample. The emerging approximate linear scaling between the MIR and X-ray luminosities, along the correlation established by Asmus et al. (2015), could be therefore considered as an indication for the nuclear (disk corona) origin of the observed X-ray fluxes also in the GPS/CSOs sample. Indeed, at least in the case of the confirmed Compton-thick objects, this is the most plausible explanation (Guainazzi et al., 2004; Siemiginowska et al., 2016; Sobolewska et al., 2019b,a). On the other hand, in the framework of the model presented in Stawarz et al. (2008) and Ostorero et al. (2010), where the X-ray radiative output of GPS/CSOs is dominated by the non-thermal emission of the compact radio lobes, one could expect some correlation between the MIR and X-ray luminosities, because in this model X-ray photons are generated predominantly by the inverse-Comptonization of the circumnuclear dust emission by relativistic electrons within compact lobes; we analyze this possibility in more detail in Appendix 2.6.1 below.

On the other hand, an approximately linear luminosity-luminosity scaling is expected in any flux limited sample of cosmologically distant sources, even in the case of no intrinsic correlations between radiative outputs in various bands (e.g., see the discussion in Singal et al., 2019). Neither our GPS/CSOs sample nor the AGN sample by Asmus et al. (2014) are, strictly speaking, flux-limited (or complete, in that matter). However, the luminosity-redshift distributions of young radio galaxies analyzed here, presented in Figure 2.8, indicate that we *are* seriously affected by flux limits in both MIR and X-ray bands, and as a result the observed luminosity-luminosity correlation may be simply due to the fact that higher- z sources have to be more luminous in either band, in order to be included in the sample.

In the lower panels of Figure 2.7, we plot again the low-resolution *WISE* $12\mu\text{m}$ and the intrinsic (absorption-corrected) 2–10 keV luminosities for our GPS/CSOs, but divided into the redshift bins $z < 0.4$ and $z > 0.4$ (left and right panels, respectively). As shown, the overall scalings are still preserved, although there is a significant difference in the luminosity ratio between the two considered redshift bins. We perform the 2D KS test for the $L_{2-10\text{keV}} - L_{12\mu\text{m}}$ distributions of our

Table 2.4. SFRs, IR luminosities, and γ -ray luminosities of 1718–649 & 1146+596

Name	$L_{8-1000\mu\text{m}}$ erg s^{-1}	SFR_{IR} $M_{\odot} \text{ yr}^{-1}$	SFR_{Ne} $M_{\odot} \text{ yr}^{-1}$	SFR_{PAH} $M_{\odot} \text{ yr}^{-1}$	$L_{0.1-100 \text{ GeV}}^{[\text{ISM}]}$ erg s^{-1}	$L_{0.1-100 \text{ GeV}}$ erg s^{-1}
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1146+596	5.5×10^{42}	~ 0.13	0.5 ± 0.1	~ 0.3	$\sim 2 \times 10^{38}$	$\sim 0.6 \times 10^{42}$
1718–649	3.7×10^{43}	~ 0.89	1.8 ± 0.1	~ 0.8	$\sim 2 \times 10^{39}$	$\sim 2 \times 10^{42}$

Note. — **col(1)** — Name of the source; **col(2)** — Integrated infrared luminosity derived from archival 8 – 1000 μm data; **col(3)** — Star formation rate for the given integrated infrared luminosity in col(2); **col(4)** — Star formation rate calculated from Ne emission lines in Willett et al. (2010); **col(5)** — Star formation rate calculated from Polycyclic aromatic hydrocarbon (PAH) emission lines in Willett et al. (2010); **col(6)** — 0.1 – 100 GeV luminosity estimated emission based on the integrated infrared flux in col(2); **col(7)** — The observed *Fermi*-LAT 0.1 – 100 GeV luminosity.

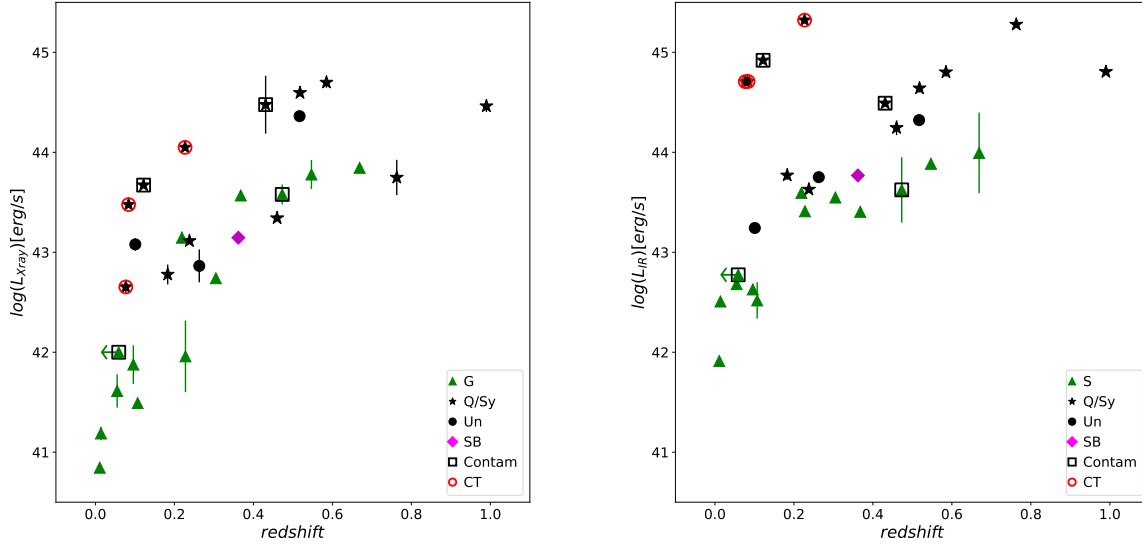


Figure 2.8: The redshift distribution of the intrinsic (absorption-corrected) 2–10 keV luminosities and the *WISE* 12 μm luminosities of our sample of GPS/CSOs (left and right panels, respectively). Symbols and colors are the same as in Figure 2.2.

GPS/CSOs and the comparison AGN from [Asmus et al. \(2014\)](#), and obtain $D = 0.26$ with $p = 0.1$ for the entire sample of young radio galaxies, $D = 0.26$ with $p = 0.25$ when only young radio galaxies at redshifts $z < 0.4$ are considered, and $D = 0.7$ with $p = 1.8 \times 10^{-4}$ for the GPS/CSOs with $z > 0.4$ (see Table 2.3). These values imply that our null hypothesis — stating that, in the “low-resolution MIR luminosity vs. absorption-corrected X-ray luminosity” representation, the GPS/CSOs and the comparison AGN samples are drawn from the same distribution — can be rejected only for high-redshift sources.

Those high-redshift targets, on the other hand, appear (visually) to match very well the best-fit correlation line of [Asmus et al. \(2015\)](#) established based on sub-arcsec MIR photometry of local AGN. This should not be surprising, however, noting that at high MIR luminosities characterizing our $z > 0.4$ sources, $L_{12\mu\text{m}} \geq 3 \times 10^{43} \text{ erg s}^{-1}$, any contribution from the ISM component with a moderate star formation rate (up to $\sim 10 M_{\odot} \text{ yr}^{-1}$), is expected to be rather minor, and so the fluxes extracted even with low-resolution instruments such as *IRAS* or *WISE*, should be dominated by the radiative output of circumnuclear dust.

On the related note, we comment that in the case of $z < 0.4$ young radio galaxies, the only ones with $L_{12\mu\text{m}}$ exceeding $10^{44} \text{ erg s}^{-1}$, are the three Compton-thick objects 1404+286, 1511+0518 and 2021+614, and the peculiar 1345+125, which can also be classified as Ultraluminous Infrared Galaxies (see [Rodríguez Zaurín et al., 2009](#)). Those four sources appear in fact over-luminous in MIR for their given intrinsic (absorption-corrected) X-ray luminosities when compared to the general local AGN population, as well as other local GPS/CSOs (see the right panel in Figure 2.8).

2.4.3 Gamma-ray Emitters 1718–649 & 1146+596

1718–649 and 1146+596 are the two lowest-luminosity sources in our sample, which are rather unique objects for several reasons. 1718–649 is particularly young and compact ($LS \simeq 2 \text{ pc}$, $\tau \simeq 100 \text{ yr}$; [Tingay et al., 1997](#); [Tingay & de Kool, 2003](#); [Giroletti & Polatidis, 2009](#)), located at the distance of 60 Mpc only, and most importantly, it is the first bona-fide CSO detected in the high-energy γ -ray range with *Fermi* Large Area Telescope (LAT; see the analysis and the discussion in [Migliori et al., 2016](#)). 1146+596 is characterized by a much larger $LS \simeq 933 \text{ pc}$ ([Taylor et al., 1998](#); [Perlman et al., 2001](#))³, but located at a comparable distance of 47 Mpc, and recently associated with the γ -ray source 4FGL J1149.0+5924 in the *Fermi* LAT 8-Year Point Source Catalog (4FGL; [Abdollahi et al., 2020](#)). The question follows if the observed γ -ray emission in both sources is related to the jet activity and compact radio lobes in particular ([Stawarz et al., 2008](#); [Kino et al., 2009](#)), or is instead due to the star formation activity within the hosts, analogous to the LAT-detected, star-forming and starburst galaxies ([Ackermann et al., 2012](#); [Hayashida et al., 2013](#); [Rojas-Bravo & Araya, 2016](#)).

³We note that 1146+596 is characterized by multiple radio outbursts, and the most compact radio component in the source, for which the kinematic age has been estimated as $\sim 60 \text{ yr}$, has a linear size of 3.5 pc ([Principe et al., 2020](#)).

In order to address this question, we have collected all archival infrared data for both sources, including near-infrared 2MASS and MIR *Spitzer* spectra, as well as mm fluxes from WMAP, and estimated the integrated 8 – 1000 μm luminosities, and next the star-formation rates assuming the [Kennicutt \(1998\)](#) scaling relation

$$\frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} = 1.7 \epsilon \times \frac{L_{8-1000 \mu\text{m}}}{10^{10} L_{\odot}}, \quad (2.2)$$

with the initial mass function factor $\epsilon = 0.79$ ([Ackermann et al., 2012](#)). The resulting values, given in Table 2.4, are consistent with the SFR estimates by [Willett et al. \(2010\)](#) for 1718–649, based on either Ne lines or PAH features in the *Spitzer* high-resolution spectra (see the Table). In the case of 1146+596 we achieve a lower SFR estimate based on the integrated luminosity, which may be due in part to poor data quality (i.e. lack of data points over the infrared range) as well as due to the fact that some MIR emission can come from the dust heated by old stellar populations and not indeed by star formation itself. As both sources are the weakest MIR emitters in the sample, the SFR at the corresponding level of $\sim 1 M_{\odot} \text{ yr}^{-1}$ should be considered as the limiting value for young radio galaxies analyzed here. Assuming further the best-fit correlation derived by [Ackermann et al. \(2012\)](#) for the LAT-detected, star-forming and starburst galaxies,

$$\log \left(\frac{L_{0.1-100 \text{ GeV}}^{[\text{ISM}]}}{10^{39} \text{ erg s}^{-1}} \right) = 1.17 \log \left(\frac{L_{8-1000 \mu\text{m}}}{10^{10} L_{\odot}} \right) + 0.28, \quad (2.3)$$

we next derived the ISM-related 0.1 – 100 GeV luminosities for the two targets, which are both at the level of $\sim 10^{38-39} \text{ erg s}^{-1}$, as listed in Table 2.4.

Meanwhile, the integrated 0.1 – 100 GeV photon flux of the high-energy γ -ray counterpart of 1718–649 provided by [Migliori et al. \(2016\)](#), $(11.5 \pm 0.3) \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}$, along with the best-fit photon index $\Gamma_{\gamma} = 2.9 \pm 0.3$, yields the luminosity $L_{0.1-100 \text{ GeV}} \sim 2 \times 10^{42} \text{ erg s}^{-1}$, which is three orders of magnitude larger than the one expected for the ISM emission as estimated above. Similarly, for 1146+596, based on the integrated 1 – 100 GeV photon flux of the high-energy γ -ray counterpart provided in 4FGL, $(2.17 \pm 0.35) \times 10^{-10} \text{ ph cm}^{-2} \text{ s}^{-1}$, along with the best-fit photon index $\Gamma_{\gamma} = 2.06 \pm 0.11$, we derive the luminosity $L_{0.1-100 \text{ GeV}} \sim 6 \times 10^{41} \text{ erg s}^{-1}$, which is again orders of magnitude larger than the expected emission for the ISM component alone.

Hence, we conclude that the γ -ray emission detected with *Fermi*-LAT from 1718–649 and 1146+596, is undoubtedly related to the jet activity in the sources, and not the star formation activity. This strengthens the expectation that compact lobes/jets in young radio galaxies are in general γ -ray emitters. Moreover, we note that the two CSOs detected by *Fermi* LAT so far, are in fact the *nearest* objects in our sample. This suggests that with a longer accumulation of the LAT data, the most promising candidates for the γ -ray detection should be 0116+319 and 0402+379 (luminosity distances $\sim 250 \text{ Mpc}$; see Table 2.1), and — even more excitingly — the two Compton-thick CSOs 1404+286 and 1511+0518 (luminosity distances $\sim 350 \text{ Mpc}$).

The existence of an intrinsic link between the X-ray and γ -ray luminosities among CSO/GPS galaxies, is still an open question, having only two such sources detected in high-energy gamma-

rays. However, theoretical modeling suggest there may be a linear correlation between the X-ray and γ -ray bands related to the radiative output of the jets in young radio sources, for further discussion see [Migliori et al. \(2014\)](#). Additional γ -ray detections of young radio galaxies could shed light on this issue and allow more conclusive statements on this relationship.

2.5 Conclusions

In this paper we have discussed the MIR properties of the most compact (GPS/CSO-type) radio galaxies, based predominantly on the lower-resolution MIR data provided by *WISE* and *IRAS* satellites (augmented in a few cases by the *Spitzer* observations). We have restricted our analysis to only those objects which have been observed in X-rays with either *XMM-Newton* or *Chandra*, and this resulted in the sample of 29 objects.

The inspection of optical images for the targets, implies that the analyzed GPS/CSOs are hosted predominantly by red/yellow galaxies with an elliptical shape, with several cases containing distorted morphology or signs of galaxy interaction.

In our sample we found a variety of *WISE* colors, suggesting that the MIR continua of the studied sources are contributed not exclusively by the circumnuclear dust, but also by the ISM of host galaxies, and in a few cases even by the non-thermal emission of compact jets and lobes. Such a diversity resembles a general population of bright local AGN ([Asmus et al., 2014](#)). In particular, we found that young radio galaxies with the MIR emission dominated by the ISM component, populate almost uniformly the entire region occupied by galaxies (from elliptical to starbursts) with a wide range of a pronounced star formation activity (rates $\geq 0.5 M_{\odot} \text{ yr}^{-1}$). This constitutes a significant difference with the population of the evolved ordinary FR II radio galaxies ([Kozieł-Wierzbowska & Stasińska, 2011](#)), which are clustered within the area of the MIR color diagram occupied by elliptical galaxies with very little star formation activity. This unexpected result — keeping in mind the general expectation that luminous CSOs are young progenitor of FR II radio galaxies — could signal a negative feedback at work, meaning that that expanding jets and lobes, during their evolution from a compact CSO phase up to the evolved classical double phase, suppress the star formation in galactic hosts. Yet we also found that the distribution of the MIR colors in our GPS/CSOs sample is statistically indistinguishable from the distribution of MIR colors of large-scale radio galaxies but with recurrent jet activity (DDRGs; [Kuźmicz et al., 2017](#)). We quantified our statement by performing two-dimensional Kolmogorov-Smirnov tests.

All these findings seems therefore to imply that (1) triggering radio jets in AGN does not differentiate between elliptical hosts with substantially different fractions of young stars, and (2) it is the jet duty cycle — and not the jet launching itself — which is related to the star formation rate within the host, in that radio galaxies hosted by galaxies with more pronounced population of young stars are either typically short lived (i.e., not surviving long enough to form an extended FR II structure), or characterized by a highly modulated/recurrent jet activity. We note in this context

that, in the accompanying paper [Wójtowicz et al. \(2020\)](#), we derived the bolometric luminosities of the accretion disks and the black hole masses for about half of the GPS/CSOs sample analyzed here, and demonstrated that the corresponding accretion rates are in all the cases high, namely between 1% and 20% in Eddington units.

The caveat here is the *WISE* color distribution of our sample of GPS/CSOs against a larger sample of double-lobed radio sources from [van Velzen et al. \(2015\)](#), suggest at the same time that the youngest radio sources avoid hosts with very vigorous starformation. However, a more plausible explanation is that there exists an observational bias which does not allow for differentiation of compact jets and lobes (and therefore for the “GPS/CSO” classification) in the presence of a strong radio emission from the central starburst region.

The distribution of the sub-sample of our sources with $z < 0.4$ on the low-resolution MIR vs. absorption-corrected X-ray luminosity plane is consistent with the distribution of a sample of local AGN on the same plane ([Asmus et al., 2014](#)). High-resolution (sub-arcsec) MIR photometry of the studied sources, along with deep X-ray exposures, are required in order to make any conclusive statements on the origin of the emerging luminosity-luminosity correlation.

Interestingly, all the confirmed Compton-thick objects in the sample — 1404+286, 1511+0518 and 2021+614 — are characterized by the *WISE* colors consistent with quasar identification, and, in addition, appear over-luminous in MIR for the given level of their intrinsic X-ray emission when compared to the general local AGN population as well as other local GPS/CSOs. Hence, *WISE* color diagnostics and photometry could, in general, be considered as a very useful tool when selecting candidates for Compton-thick AGN among compact radio galaxies. Note in this context that, compact radio sources are particularly abundant in flux-limited radio samples, constituting $\sim 10\%$ of the bright radio-source population ([O’Dea, 1998](#); [Sadler, 2016](#)).

Finally, we discussed in more detail the particular case of the γ -ray-detected 1718–649 and 1146+596. By means of a comparison with the sample of star-forming and starburst galaxies detected with *Fermi*-LAT, we have argued that the γ -ray flux observed from these, is undoubtedly related to the jet activity in the sources, and not due to the star formation activity. This strengthens the expectation that compact lobes/jets in young radio galaxies are in general γ -ray emitters, albeit relatively weak so that the *Fermi*-LAT detections are currently limited to the two the nearest objects in the sample.

2.6 Appendix

2.6.1 Non-thermal X-ray Emission of Young Radio Galaxies

Below we provide a very simplified approximation for the expected X-ray luminosity of compact radio lobes in compact radio galaxies, following [Stawarz et al. \(2008\)](#). In this model, the monochromatic lobes' luminosity is

$$\varepsilon L_\varepsilon \simeq \frac{2}{3} c \sigma_T V U_{\text{MIR}} \left[\gamma^3 N_e(\gamma) \right]_{\gamma=\sqrt{\varepsilon/\varepsilon_0}}, \quad (2.4)$$

where V is the volume of the lobes, U_{MIR} is the energy density of the circumnuclear dust emission at the position of the lobes, $N_e(\gamma)$ is the energy spectrum of ultrarelativistic electrons with Lorentz factors γ , and ε_0 is the energy of the Compton-upscattered seed photon. By following the evolution of the electrons subjected to radiative and adiabatic energy losses within the expanding lobes, [Stawarz et al. \(2008, section 3.1. therein\)](#) showed that in the case of a single power-law injection rate $Q_e(\gamma) = k \gamma^{-s}$ with $s \geq 2.0$ and the normalization constant k , for a given age of a source τ the electron spectrum can be approximated by $N_e(\gamma) \simeq \tau (k/V) \times f(\gamma)$, where $f(\gamma) = \gamma^{-s}$ for $\gamma < \gamma_{\text{cr}}$ and $f(\gamma) = \gamma_{\text{cr}} \gamma^{-s-1}$ otherwise, and $\gamma_{\text{cr}} \propto L_j^{-1/2}$ is the cooling break energy depending on the jet's total kinetic luminosity L_j . We further assume an energy equipartition between ultrarelativistic electrons and the lobes' magnetic field, meaning $V U_e \simeq \tau L_j$, where $U_e \equiv \int \gamma m_e c^2 N_e(\gamma) d\gamma$ is the electron energy density. Note that $\tau = \text{LS}/v_h$, where LS is the linear size of the lobes, taken as the distance between the jet termination shocks (hereafter “hotspots”) in a given source, and v_h is the expansion velocity of the lobes, measured as the separation velocity between the hotspots.

For the seed photon's energy density at the position of the lobes, we simply take $U_{\text{MIR}} \simeq L_{\text{MIR}}/4\pi R^2 c$, where $R \simeq (\sqrt[3]{3}/8) \text{LS}$ is the effective radius of the lobes, approximated as an ellipsoid with a semi-major axis $a = \text{LS}/2$ and semi-minor axis $b = a/4$ (see in this context [Kawakatu et al., 2008](#); [Wójtowicz et al., 2020](#)), and $L_{\text{MIR}} \sim 3 \times L_{12\mu\text{m}}$ is the total MIR luminosity of the hot dusty torus, with a mean photon energy $\varepsilon_0 = hc/\lambda_0$ for $\lambda_0 \sim 12\mu\text{m}$. Given all the above, one may find

$$\frac{L_{2-10\text{keV}}}{L_{12\mu\text{m}}} \simeq \frac{32 \sigma_T}{3^{2/3} \pi m_e c^2} \frac{L_j}{v_h \text{LS}} \frac{\int_2^{10} [\gamma^3 f(\gamma)]_{\gamma=\sqrt{\frac{x}{x_0}}} \frac{dx}{x}}{\int_1^{1e5} \gamma f(\gamma) d\gamma}, \quad (2.5)$$

where $x \equiv \varepsilon/\text{keV}$. We next note, for the injection index $s = 2.5$ corresponding to the mean radio spectral index of compact radio galaxies ([de Vries et al., 1997](#)), the last term in the above relation containing integrals over $f(\gamma)$, depends only weakly on the jet kinetic power, and within a wide range of L_j reads as ~ 20 . Hence, a very simple approximate scaling emerges

$$\frac{L_{2-10\text{keV}}}{L_{12\mu\text{m}}} \sim \left(\frac{L_j}{10^{45} \text{erg s}^{-1}} \right) \left(\frac{\text{LS}}{\text{pc}} \right)^{-1} \left(\frac{v_h}{c} \right)^{-1}. \quad (2.6)$$

One should keep in mind that the scaling relation derived above relies on several crude approximations, in particular the spectral shape of the electron injection function, so it is possible

that in several cases a more detailed modelling, taking into account the exact shape of the radio continua of the studied sources (as presented in [Ostorero et al., 2010](#)), could result in an elevated level of the expected inverse-Compton emission of compact lobes in the X-ray domain. Additionally, the true jet kinetic luminosities may be larger than the minimum values utilized here. Keeping all these caveats in mind, we conclude that a significant contribution of the non-thermal emission of compact lobes to the observed radiative output of compact radio galaxies in the X-ray domain, remains a plausible option, and that the resulting X-ray luminosity should scale with the MIR luminosity of dusty tori, albeit with a wider scatter due to the dependence of the $L_{2-10\text{ keV}}/L_{12\mu\text{m}}$ ratio on the jet kinetic luminosity L_j , the linear size of radio lobes, and the expansion velocity of compact lobes v_h .

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Chapter 3

Spectroscopic Diagnostics of the Mid-Infrared Features of the Dark Globule, DC 314.8–5.1, with the Spitzer Space Telescope

This chapter originally appeared as ‘Spectroscopic Diagnostics of the Mid-Infrared Features of the Dark Globule, DC 314.8–5.1, with the Spitzer Space Telescope’ by E. Kosmaczewski et al. 2022, The Astrophysical Journal, Volume 934, Issue 2, article id. 94 ([Kosmaczewski et al., 2022b](#))

Abstract

We present an analysis of the mid-infrared spectra, obtained from the Spitzer Space Telescope, of the dark globule, DC 314.8–5.1, which is at the onset of low-mass star formation. The target has a serendipitous association with a B-type field star, which illuminates a reflection nebula in the cloud. We focus on the polycyclic aromatic hydrocarbon (PAH) emission features prevalent throughout the mid-infrared range. The analysis of the spectra with the PAHFIT software as well as pypahdb package, shows that (i) the intensities of PAH features decrease over distance from the ionizing star toward the cloud center, some however showing a saturation at larger distances; (ii) the relative intensities of the 6.2 and 8.6 features with respect to the 11.2 μm feature remain high throughout the globule, suggesting a larger cation-to-neutral PAH ratio of the order of unity; the breakdown from pypahdb confirms a high ionized fraction within the cloud; (iii) the pypahdb results display a decrease in large PAH fraction with increased distance from HD 130079, as well as a statistically significant correlation between the large size fraction and the ionized fraction across the globule; (iv) the 7.7 PAH feature displays a peak nearer to 7.8 μm , suggesting a chemically processed PAH population with a small fraction of UV-processed PAHs; (v) the $\text{H}_2 \text{S}(0)$ line is detected at larger distances from the ionizing star. All in all, our results suggest divergent physical conditions within the quiescent cloud DC 314.8–5.1 as compared to molecular clouds with ongoing starformation.

3.1 Introduction

Polycyclic Aromatic Hydrocarbons (PAHs), containing tens to hundreds of carbon atoms, are an abundant and ubiquitous component of the interstellar medium (ISM); although they are found in many different systems, ranging from molecular clouds in the Milky Way to distant active galaxy nuclei, their origin and distribution are not fully understood (see, e.g., reviews by [Tielens, 2008](#); [Joblin & Tielens, 2011](#); [Li, 2020](#)). PAHs can be observed via their infrared (IR) fluorescence through the vibrational modes, manifesting in particular in broad emission features at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm . This, however, heavily relies on ultraviolet (UV) radiation for excitation, and therefore quiescent properties of PAHs remain elusive.

There has been extensive modeling of PAHs in various environments, attempting to disentangle contributions of molecules with different sizes, charge states, or even structure and content, to the IR radiative output at different wavelengths. It was shown that the 3.3 and 11.3 μm features are predominantly due to neutral PAHs, while the 6.2, 7.7, and 8.6 μm features are dominated by ionized PAHs; relative intensity of the 6.2 and 7.7 μm features, on the other hand, were argued to be sensitive to the number of carbon atoms in a molecule (e.g., [Draine & Li, 2001](#)). Hence, the intensity ratio diagram “6.2/7.7 versus 11.3/7.7” was widely considered as a diagnostic tool enabling constraints on the distributions of PAH sizes and ionization states in various astrophysical sources, especially in ones that can be spatially resolved by IR spectrometers (see [Berné et al., 2007](#); [Visser et al., 2007](#); [Pineda & Bensch, 2007](#); [Rosenberg et al., 2011](#); [Peeters et al., 2017](#); [Boersma et al., 2018](#)). More recently, however, other intensity ratios, such as 11.2/7.7 and 11.2/3.3, have been considered as more reliable proxies for the main characteristics of the PAH population, with the 3.3 feature being particularly sensitive to the number of carbon atoms in a molecule ([Maragkoudakis et al., 2020](#)).

The key factors determining the plasma ionization, in addition to the amount of the exciting emission, are the gas electron density and temperature. At the same time, the size distribution of PAHs is expected to be shaped by the ionizing continuum, as well as shocks possibly present in a system ([Boersma et al., 2014](#); [Li, 2020](#); [Verstraete, 2011](#); [Siebenmorgen & Krügel, 2010](#)). As a result, in star-forming regions — which are the typical targets for resolved IR spectroscopy — PAHs undergo significant processing at early stages of the systems’ evolution, and so there is an observational bias in regards to probing the dust and PAH conditions in these systems following the onset of star formation.

Yet, the emission produced in the surroundings of young stars, is not the only agent capable of ionizing the ISM or of causing grain destruction. In fact, lower-energy cosmic rays are often considered as an equally relevant source of ionization, in particular in the context of dense molecular clouds and the Galactic Center region (e.g., [Prasad & Tarafdar, 1983](#); [Padovani et al., 2009](#); [Caselli et al., 2012](#); [Indriolo & McCall, 2013](#); [Indriolo et al., 2015](#)). In this context: large PAHs can substantially modify the ionization balance in their environment via a charge transfer from interstellar ions (leading to the creation of PAH cations), or electron attachment (producing PAH

anions), and subsequent mutual neutralization (Bakes & Tielens, 1998; Dalgarno, 2006; Verstraete, 2011). In addition cosmic rays should be also considered as a relevant agent responsible for destroying PAHs, especially the smaller ones, and especially in dense clouds, where the competing processes of PAH destruction by interstellar shocks or UV emission, are rather inefficient (Micelotta et al., 2011).

In this paper, we discuss the PAH features of a region in at the eastern edge of DC 314.8–5.1, mapped with the Spitzer Space Telescope (Werner et al., 2004). Our work is motivated by the previous study by Whittet (2007), who identified the system as a compact and dense “dark globule”, at the onset of low-mass star formation (see in the context the review by Bergin & Tafalla, 2007). The distance and the parameters that depend on distance, could be constrained relatively precisely by the serendipitous association of the cloud with a B-type field star, which illuminates a reflection nebula near its eastern boundary. The Spitzer Space Telescope observations analyzed here, provide us the opportunity to also study the PAH features, at varying distance from the star, and at the same time from the center of the globule. In this way, we seek to diagnose the ionization level conditions and the dust grain distribution within the dense molecular cloud, *before* any formation of stars, and so not affected by the presence of young stellar objects.

The paper is organized as follows. In the next Section 3.2, we summarize the established properties of the DC 314.8–5.1. In the following Section 3.3, we introduce the Spitzer Space Telescope observations targeting the system, and next in Section 3.4 we discuss the analysis performed on the Spitzer data. In Section 3.5 we present the analysis results regarding the PAH features and ratios; these results are further discussed in Section 3.6 and concluded in the final Section 3.7.

3.2 System Overview

DC 314.8–5.1 is a dark globule $\sim 8' \times 5'$ in angular size, located approximately 5 degrees below the Galactic Plane, RA(J2000) = 14h 48m 29.00s, Dec(J2000) = $-65^\circ 15' 54.0''$, in the constellation of Circinus; see Figure 3.1. The system was originally identified in the Hartley et al. (1986) catalogue of southern dark clouds and was selected from that catalogue for further study. The globule is of particular interest due to the association of field star, HD 130079, embedded in its eastern boundary. HD 130079 is a 10^{th} magnitude, normal main sequence star, with a well-established spectral type of B9V (Whittet, 2007, and references therein); it is illuminating a reflection nebula on the eastern boundary of the cloud.

The association of the star HD 130079 with DC 314.8–5.1 allows important physical characteristics of the system to be estimated. A review of the physical properties of HD 130079 and the dust responsible for extinction in the line of sight was carried out by Whittet (2007), with the goal of better constraining the distance to the star (and hence, to the cloud). Since this work was completed, new and far more accurate constraints on the distance to HD 130079 have become available as the result of parallax measurements by the Gaia mission. The parallax value for the star in the EDR3

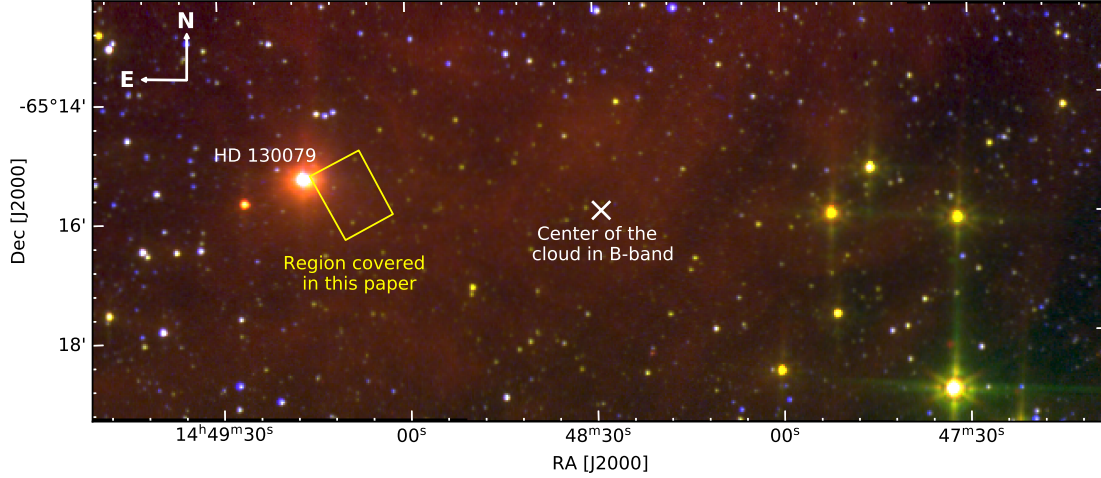


Figure 3.1: RGB image with a horizontal angular size of $\sim 17'$ and a vertical angular size of $\sim 7'$, centered on the dark globule, DC 314.8–5.1. The red, green and blue colors are taken from Spitzer/IRAC ($8.0\,\mu\text{m}$, and $5.8\,\mu\text{m}$), and DSS1 blue band, respectively. The images are combined utilizing the APLpy package v2.0.2 (Robitaille & Bressert, 2012; Robitaille, 2019). HD 130079 can be identified as the bright star located left of center in the eastern boundary of the globule. The globule is the diffuse region in the center, obscuring and reddening the background starlight.

data release (Gaia Collaboration et al., 2021) is 2.2981 ± 0.0194 mas. This result corresponds to a distance of 435 ± 4 pc, placing it at a significantly greater distance compared with the photometric estimate of 342 ± 50 pc deduced by Whittet (2007). The most likely cause of the discrepancy is an over-estimate of the ratio of total to selective extinction in the earlier work, possibly resulting from contamination of the photometry by a fainter, redder star in the aperture. With the revised distance, the angular dimensions of the dark cloud ($\sim 8' \times 5'$; Figure 3.1) correspond to a projected linear size of $\sim 0.9\,\text{pc} \times 0.6\,\text{pc}$. Using this result and other observed properties of the dark cloud, the mean core number density of hydrogen gas is $\sim 10^4\,\text{cm}^{-3}$, and the total mass of the cloud is $\sim 160M_{\odot}$ (see Hetem et al., 1988; Whittet, 2007).

DC 314.8–5.1 appears to be in a quiescent state prior to the start of star formation. There has been significant interest in verifying the validity of these so called “starless cores”, but according to a study performed by Kirk et al. (2007) the probability of a misidentified core (i.e. that a “starless core” is not in fact starless but host to some stellar object) is low ($\sim 5\%$). Proper verification for a starless core can be performed by utilizing the Multiband Imaging Photometer (MIPS) onboard the Spitzer Space Telescope, to search for sources embedded in a system (Kirk et al., 2007). A stellar consensus utilizing the Two Micron All-Sky Survey (2MASS; Skrutskie et al., 2006) yielded only two potential Young Stellar Object (YSO) candidates in DC 314.8–5.1, one of which was excluded as a old star with significant dust reddening, out of a sample of 387 sources (Whittet, 2007). The globule, therefore, was determined *not* to be a site of vigorous star formation, and as such is a valuable system to study the dynamics of a pre-stellar globule.

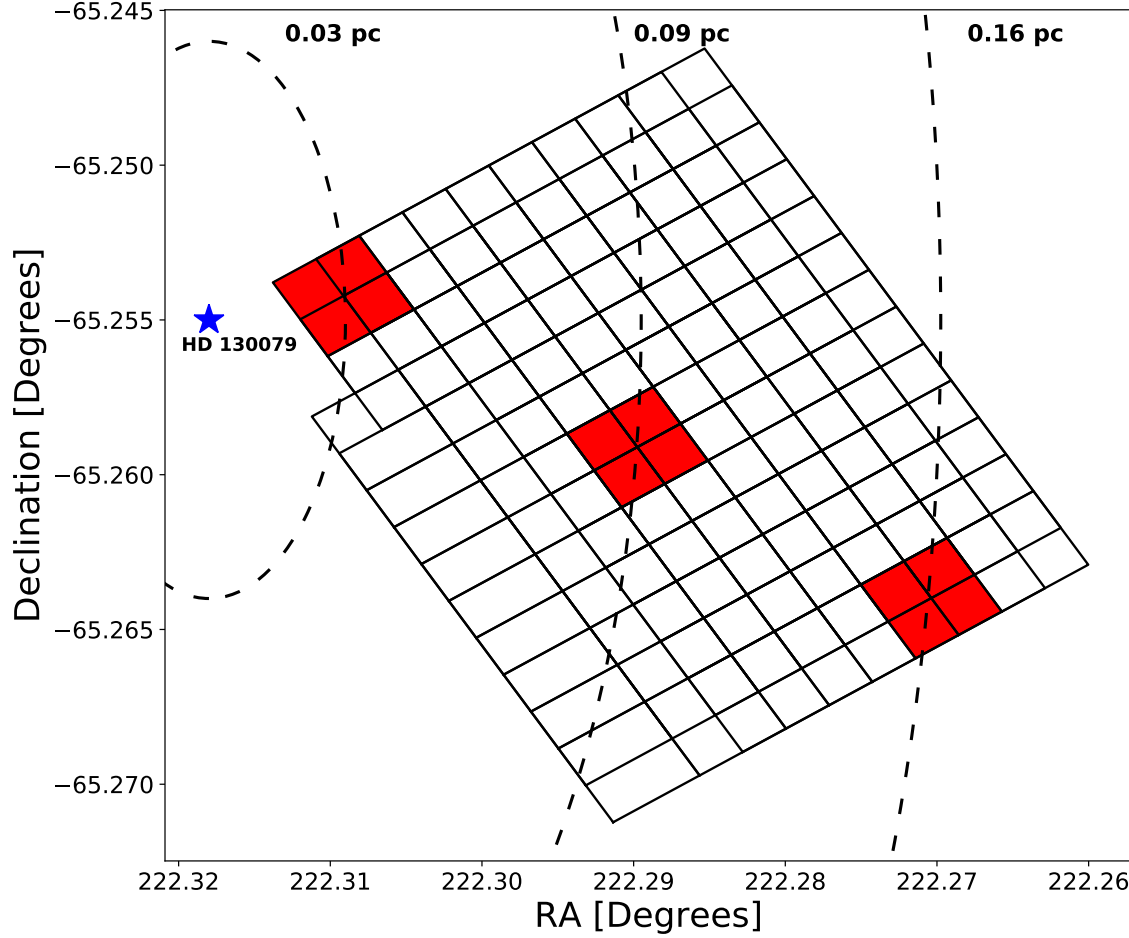


Figure 3.2: 117 overlapping Spitzer IRS MAP MIR spectroscopic regions extracted from the eastern boundary of DC 314.8–5.1, with increasing distance from HD 130079. Extraction regions are overlapping to better account for subtle changes in features over distance. Red shaded regions mark three of the extraction regions which correspond to the spectra given in Figure 3.3, with respective distance arcs marked by dashed lines. Each cube spans 2×2 pixels with an angular width of $\sim 5''$ per pixel, which at a distance of 435 ± 4 pc (a systematic error of less than 1%) translates to a spatial size of a box width of ~ 0.02 pc ($\sim 10''$). The observational center of the cloud is positioned at RA(J2000) = 14h 48m 29.00s, Dec(J2000) = $-65^\circ 15' 54.0''$, with a projected distance of ~ 0.63 pc from HD 130079. Spectral regions range from a distance of ~ 0.03 to ~ 0.18 pc from HD 130079.

3.3 Spitzer Observations

Observational data for this work were provided by the Spitzer Space Telescope (Proposal ID 50039; P.I.: D. Whittet), acquired by the InfraRed Spectrograph (IRS; Houck et al., 2004) Mapping mode of the reflection nebula near the field star HD 130079. The IRS mapping observations, obtained through the Spitzer Heritage Archive, are used to investigate the relationship between the radiation from the field star and the corresponding PAH features within the globule.

IRS mapping observation of the reflection nebula was obtained in both the short-low (SL) and long-low (LL) modules of IRS and covers the wavelength range of 5.13 to 39.0 μm . These data have a resolving power of ≈ 60 –127 and a signal-to-noise ratio $S/N \approx 20$. We achieve the high S/N in a relatively short amount of time: 2×60 s in SL and 2×14 s in LL. The slits are overlapped by 1/2 of the slit dimensions in both directions which mitigates artifacts due to bad and rogue pixels and results in a reduction of errors in flat-fielding.

3.4 Data Analysis

3.4.1 Reduction of Data Products

The data reduction procedure for the SL and LL spectroscopic data followed was similar to the CUBISM recipe outlined in the Spitzer Data Cookbook¹, Recipe 10, with parameters appropriate for our dataset. The CUBISM standard bad pixel generation was applied with the following values: $\sigma_{trim} = 7$, minimum bad-fraction equal to 0.5 for global bad pixels and equal to 0.75 for record bad pixels. Due to the source being a low luminosity object, additional bad pixels were flagged visually before spectral extraction. 117 extraction regions were defined of dimensions 2×2 pixels around the field star, HD 130079, within the reflection nebula, as visualized in Figure 3.2. Regions were selected such that the center of each new region was the edge of the previous region to account for subtle changes over distance. Spectral extraction was performed by selecting a region beginning on the star, of four pixels, and shifting the extraction region one pixels for each new extraction (in both vertical and horizontal directions). Projected distances from the field star were calculated from the center of each selection cube. Each cube (i.e., each array of four neighbouring pixels, see Figure 3.2), spans an angular width of $\sim 10''$, which at a distance of 435 ± 4 pc (a systematic error of less than 1%) translates to a spatial size of ~ 0.021 pc. In order to extract spectra for the entire wavelength range, four cubes were built for each spatial extraction region, one for each spectral mode (i.e. SL1, SL2, LL1, LL2) (Smith et al., 2007a).

The combination of spectral modes (i.e. SL1, SL2, LL1, and LL2) was performed utiliz-

¹<https://irsa.ipac.caltech.edu/data/SPITZER/docs/>

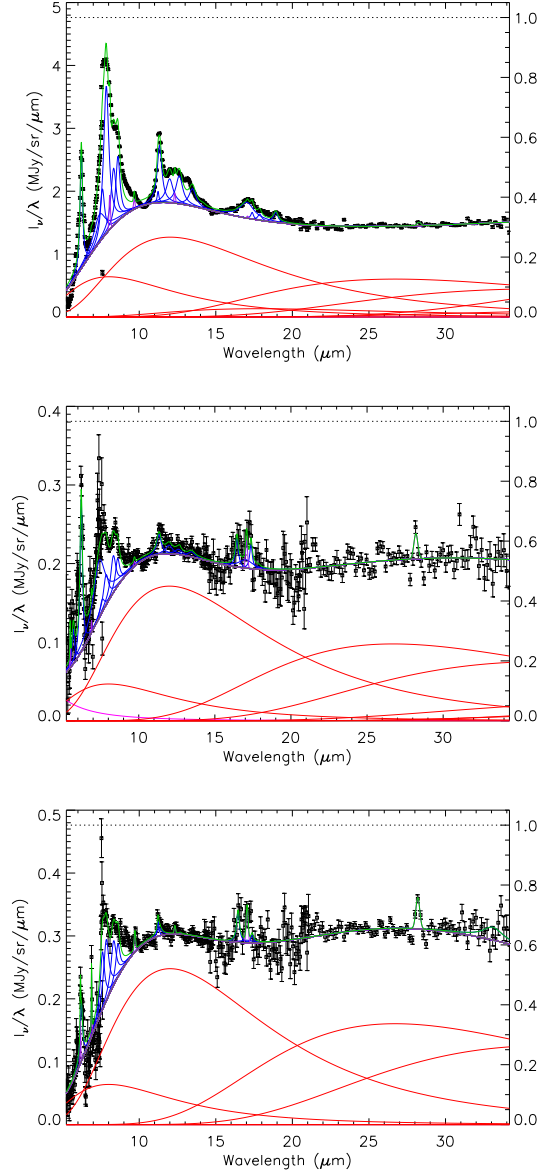


Figure 3.3: Fully fitted spectra extracted from the three regions at the projected distances of 0.03 pc, 0.09 pc, and 0.16 pc away from the illuminating field star, HD 130079 (upper, middle, and lower panels, respectively), see Figure 3.2 for the physical extent of the extraction regions for each spectra. Spectral fitting of the regions was performed with PAHFIT (Smith et al., 2007b). The green curve represents the best fit, red curves represent the thermal dust continuum components, thick gray curves indicate the total dust and stellar continuum, blue curves indicate the fitted PAH features, violet curves indicate atomic and molecular spectral lines, and green curves represent the fully fitted model. The dotted black curves (present in the middle and bottom panels) denotes the level of extinction (fully mixed) present (relative fraction presented on the right vertical axis).

ing python coding routines, developed with Python (3.5.9 distribution²), and standard averaging methods involving propagation of errors. Differences in the continuum of the SL and LL modes (prevalent in low-intensity regions) were taken into account by scaling the LL modes to the SL modes.

3.4.2 Fitting Process for Data Products

Spectral decomposition of the IRS Map observations was performed with the PAHFIT spectral fitting software (Smith et al., 2007b). PAHFIT utilizes a model consisting of starlight, thermal dust continuum in fixed temperature bins, resolved dust features, prominent emission lines, and silicate dust extinction. This fitting was performed on all 117 extracted low resolution spectra taken at varying distances away from HD 130079 (and therefore increasing distance to the cloud center; see Figure 3.2). The PAHFIT process results in images for each fit as well as text files denoting the central wavelength, intensity, and the respective errors for each line fit, and also levels for stellar and dust continuum fits. Specifically PAHFIT measures the Starlight, Dust Continuum at 300, 200, 135, 90, 65, 50, 40, and 35 degrees Kelvin, 18 emission lines (H₂, Ar, S, Fe, Si, and Ne), 25 Drude profiles to fit the PAH features, and the extinction level. Due to the high excitation for the atomic lines, we do not expect/nor do we see any evidence of their presence in our sample and so all atomic lines are removed by fixing their normalization to zero during the fitting procedure (see Herbst & van Dishoeck, 2009).

Figure 3.3 shows for illustration the three spectra extracted at three various distances from the star, after PAHFIT fitting. Data points are presented by black squares (with respective error bars), red curves indicate the stellar continuum, thick gray curves indicate the dust and stellar continuum, blue curves indicate the fitted dust features, violet curves indicate atomic and molecular spectral lines, the dotted curves indicate components diminished by fully mixed extinction, and the green curves represent the fully fitted model (Smith et al., 2007b). As is evident in Figure 3.3, the 5 – 20 μm range is dominated by emission features, whereas the spectrum is almost featureless at longer wavelengths; we therefore focus on the 5 – 20 μm spectrum in the following sections. Specifically we note the strong ionized 6.2 and 7.7 μm features, as well as the ionized 8.6 μm feature, in addition to a strong 11.2 – 11.3 μm neutral PAH feature.

Complementary fitting of the extracted spectra were performed utilizing the pypahdb³ package (Matthew J. Shannon & Christiaan Boersma, 2018). Unlike the PAHFIT routine, which decomposed the 5–35 μm low-resolution Spitzer spectra into the dust continuum emission (modeled as a superposition of modified blackbodies), PAH features (fitted with phenomenological Drude profiles), and atomic/molecular lines (approximated as Gaussians), the pypahdb package utilizes the

²<https://docs.python.org/3/>

³<https://pahdb.github.io/pypahdb/>

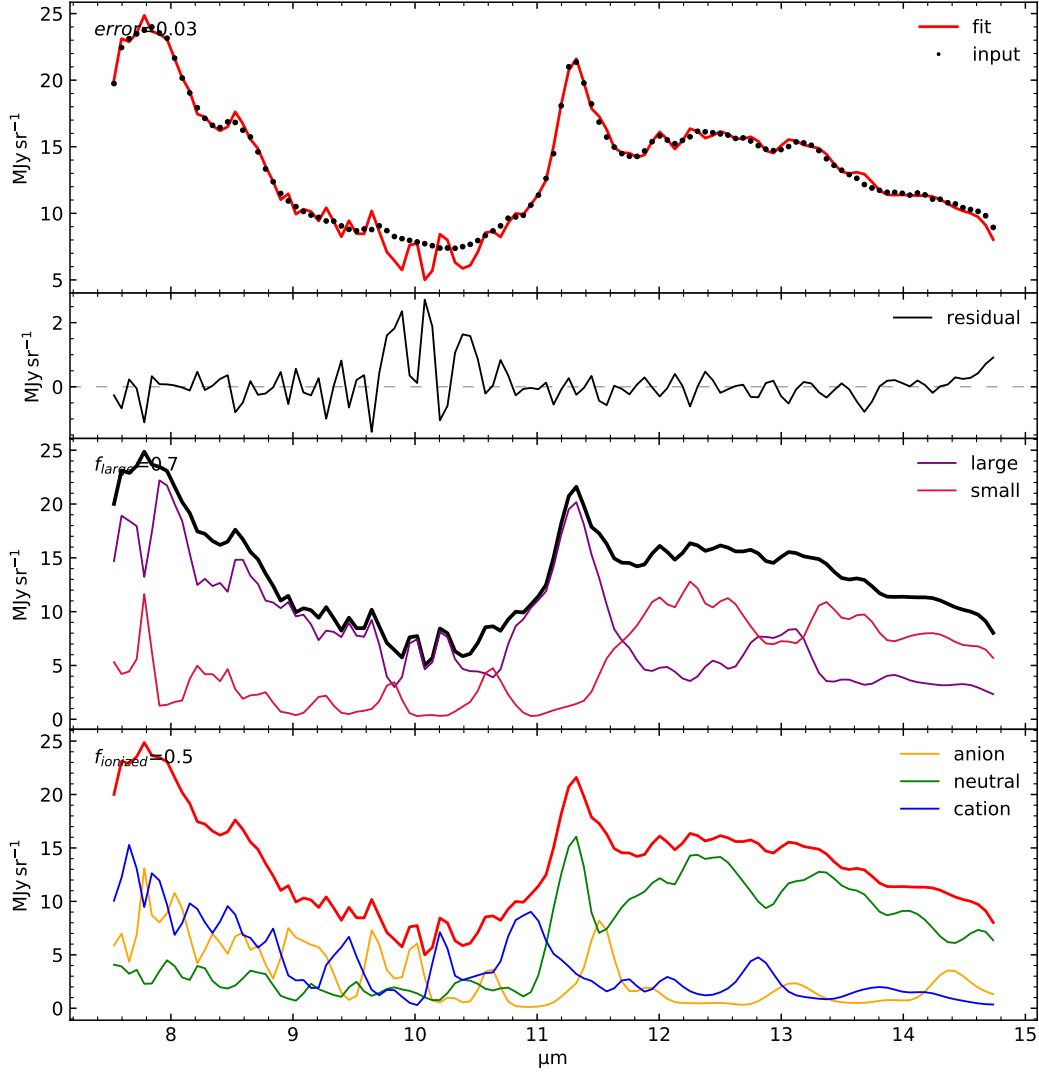


Figure 3.4: Pypahdb (Matthew J. Shannon & Christiaan Boersma, 2018) fit of the SL1 mode from the nearest spectral region to HD 130079 at a projected distance of 0.03 pc. From top to bottom the individual panels represent: the fully fitted spectrum with data points marked as black dots with respective errors, note here that error bars are significantly small as to not be easily visible, residuals in the final fit, the breakdown of the PAH species sizes into large ($N_C > 40$) and small species, and the breakdown of the cation, neutral, and anion species.

NASA Ames PAH IR Spectroscopic Database (see [Matthew J. Shannon & Christiaan Boersma, 2018](#), for an updated summary), to directly extract the ionization fraction and the size breakdown for the PAH molecules within the analyzed region by means of fitting the observed spectrum against the library of computed PAH spectra which contains data on thousands of PAH species.

For our study, we utilized pypahdb for each of our sampled regions for the Spitzer SL1 mode (i.e. $7.5\text{--}15\ \mu\text{m}$). We do not include the SL2 mode in this fitting as the inclusion of the additional segment from SL2 ($6.5\text{--}7.5\ \mu\text{m}$) greatly reduces the quality of the fit, increasing residuals to $> 10\ \text{MJy sr}^{-1}$. Figure 3.4, presents the pypahdb fit for the extraction region located nearest to the field star, HD 130079, at a distance of 0.03 pc, showing the respective breakdown of ionization and size, where large species are defined as $N_C > 40$. The resulting spectral fits have a high SNR > 5 , with only five regions having $5 > \text{SNR} > 3$, and only one region had an average residual equating a SN lower than 3σ and as such was removed from any further analysis.

3.4.3 Extraction of Intensity Maps

Intensity maps were extracted from the Spitzer spectral cubes with Cubism for selected features ([Smith et al., 2007a](#)). For each map the continuum is defined as the regions on either side of the feature, and removed, taking particular care in this procedure to not include any neighbouring features or lines. The peak of the desired feature is then selected. This procedure produces a continuum-subtracted map of the averaged surface brightness in units of MJy sr^{-1} . In Figure 3.5 we present the resulting 6.2 , 7.7 and $11.3\ \mu\text{m}$ PAH feature maps, created by defining the feature with ranges for each peak as follows: $6.0\text{--}6.5\ \mu\text{m}$, $7.3\text{--}7.9\ \mu\text{m}$, $11.2\text{--}11.4\ \mu\text{m}$.

3.4.4 Extinction Profile

For the inspection of line features within the dark globule, DC 314.8–5.1, it is important to comment on the extinction within the sampled region. Given in [Whittet \(2007\)](#) the lower limit of the extinction of the cloud core is $A_V \gtrsim 8.5\ \text{mag}$, however, this is not the region that is sampled in our study. We are investigating the outskirts of the cloud from $0.03\text{--}0.18\ \text{pc}$ projected distance from HD 130079, which corresponds to a distance range from the core of DC 314.8–5.1 of $0.3\text{--}0.45\ \text{pc}$. Given however the extinction of 8.5 in the core of the cloud, the established relation $N_{H_2}/A_V \simeq 9.4 \times 10^{20}\ \text{cm}^{-2}\ \text{mag}^{-1}$ ([Hetem et al., 1988](#)), and assuming the standard mass density profile for the cloud $\rho(r) \propto r^{-1.3}$ ([Cernicharo et al., 1985](#)), we can estimate the extinction level within a certain distance probed in this paper, namely $0.3\text{--}0.45\ \text{pc}$ from the center of the cloud, as $1.0\text{--}1.8\ \text{mag}$ (corresponding to the H_2 column density of $\sim 1.0 - 1.7 \times 10^{21}\ \text{cm}^{-2}$). The extinction within the sampled distances can therefore affect the PAH emission of the cloud, although we should still be able to probe the full depth of the targeted segment of the system. Obviously, given the simplicity of the above-mentioned estimate, it is possible that the extinction in this region may be higher and we may only be seeing the surface of the cloud contributing to the PAH emission seen.

Table 3.1. PAH Drude Profiles

Feature	Wavelength [μm]	Max Intensity [MJy sr $^{-1}$]
The “Inverse Power-law” Category		
PAH 6.2	6.22	12.3 ± 0.002
PAH 7.4	7.42	4.26 ± 0.009
PAH 11.3	11.3	10.2 ± 0.003
The “Inverse Power-law + Plateau” Category		
PAH 7.6	7.6	5.39 ± 0.010
PAH 7.8	7.85	18.5 ± 0.002
PAH 8.3	8.33	7.69 ± 0.003
PAH 8.6	8.61	8.84 ± 0.003
PAH 11.2	11.2	2.05 ± 0.023
PAH 17.0	17.0	4.67 ± 0.020
PAH 17.9	17.8	2.06 ± 0.046
PAH 18.9	18.9	3.46 ± 0.028

Note. — **Col(1)** — PAH Drude profile designation; **Col(2)** — Central wavelength as fit by PAHFIT; **Col(3)** — Maximum intensity out of the 117 regions as fit by PAHFIT.

Table 3.2. Integrated PAH Features

Feature	Wavelength [μm]	Max Power [Wm $^{-2}$ sr $^{-1}$ $\times 10^{-9}$]
The “Inverse Power-law” Category		
PAH 6.2	6.2 – 6.3	279 ± 1.38
PAH 11.3	11.2 – 11.4	146 ± 0.712
The “Inverse Power-law + Plateau” Category		
PAH 7.7	7.3 – 7.9	1070 ± 5.41
PAH 8.6	8.6 – 8.7	189 ± 1.35
PAH 17.0	16.4 – 17.9	99.5 ± 2.87

Note. — **Col(1)** — PAH feature designation; **Col(2)** — Central wavelength as fit by PAHFIT; **Col(3)** — Maximum power measured out of 117 regions as fit by PAHFIT.

3.5 Results

3.5.1 Trends & Progressions

To a first approximation, one might expect a rather uniform distribution of PAH molecules within the relatively small region covered by the IRS mapping, and therefore that the PAH feature emission reflects, solely, the level of the ionizing continuum radiation. In other words, any spatial variation in the PAH features would be expected to be directly related to the emission of HD 130079, which is the dominate source of the UV photon flux within the sampled regions of the cloud and as such should decrease with projected distance from the star. However, trends in the feature intensities and intensity ratios observed in DC 314.8–5.1, appear to be more complex. Below we inspect the individual fitted Drude profiles, along with the integrated PAH features, over distance. In the inspection of features only those with a SNR greater than 3 in at least 20% of the regions are included; here the SN was calculated as, simply, the ratio of the fitted intensity of a given feature over the error in the fit.

First we inspect the individual Drude profile fits from PAHFIT over distance. The resulting trends can be generally divided into two major categories: in particular, as shown in Figure 3.6 and summarized in Table 3.1, we see either the single “inverse power-law” scaling, or the “inverse power-law + plateau” trend, i.e. the inverse power-law behavior until a certain distance where the feature flattens out.

The individual PAH features can have multiple Drude profiles contributing to them, and so for such, their integrated strength should be inspected rather than the individual Drude profiles. This regards in particular the five main PAH features, namely 6.2, 7.7, 8.6, 11.3, and $17.0\,\mu\text{m}$, for which their respective trends are given in the Figure 3.7. As follows the previous discussion, here the “power-law” and “power-law + plateau” categories are also represented. Note that for the integrated power trends we consider only the well-defined PAH features, excluding in particular the $8.3\,\mu\text{m}$ feature for which PAHFIT returns a high-significant detection in terms of the Drude profile intensity (see Figure 3.6 and Table 3.1), even though this feature may be rather due to the blending of the neighbouring 7.7 and 8.6 features (see the discussion in [Peeters et al., 2017](#)).

3.5.2 Individual Features and Lines

Figure 3.8 presents a zoom to the fully-fitted $5.5 - 30.0\,\mu\text{m}$ segment of the spectrum for the region located at 0.03 pc projected distance from HD 130079 (see the upper panel in Figure 3.3), highlighting the region which encompasses the majority of features. As shown, various profiles can contribute to single spectral features, and only by means of a detailed spectral fitting can one disentangle them. In the presentation of individual profiles we adopt the high significance/prevalence criteria, namely, $\text{SNR} > 5$ detections in at least 20% of the regions. Figure 3.9 presents a more

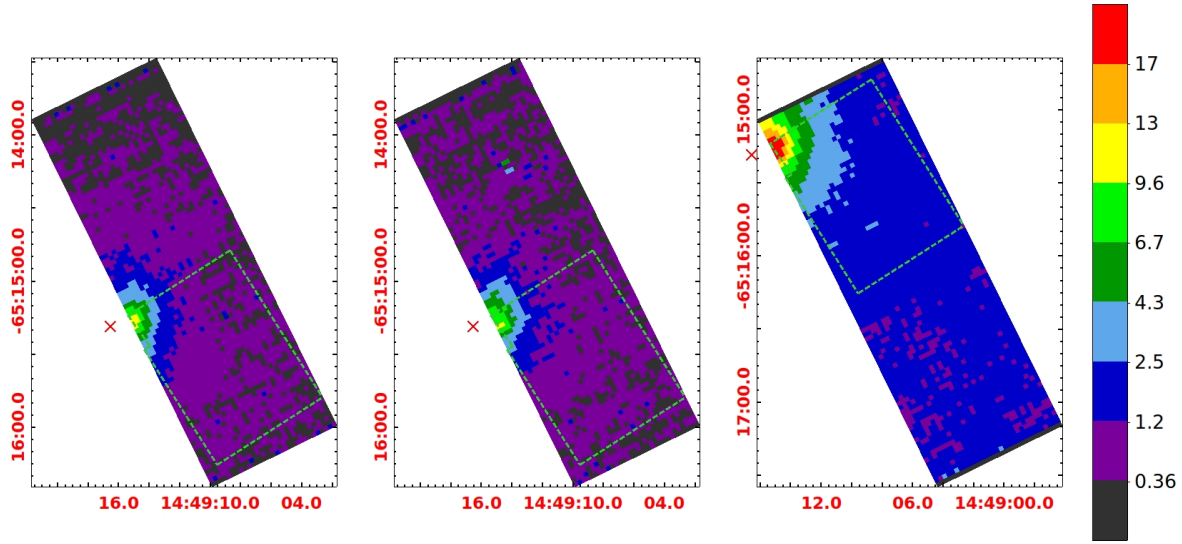


Figure 3.5: Square root scaled intensity maps of the continuum-subtracted PAH features: 6.2 (left), 7.7 (middle), and 11.3 μm (right). The colorbar is set with a range across all the features from 0.1–21.5, with the maximum set by the 11.3 μm feature and the minimum intensity set by the 6.2 μm feature map. In all images orientation is the same as in Figure 3.1, North is orientated up and East is orientated to the left. The green dashed lines delineate the extraction regions with the red cross indicating the optical center of HD 130079.

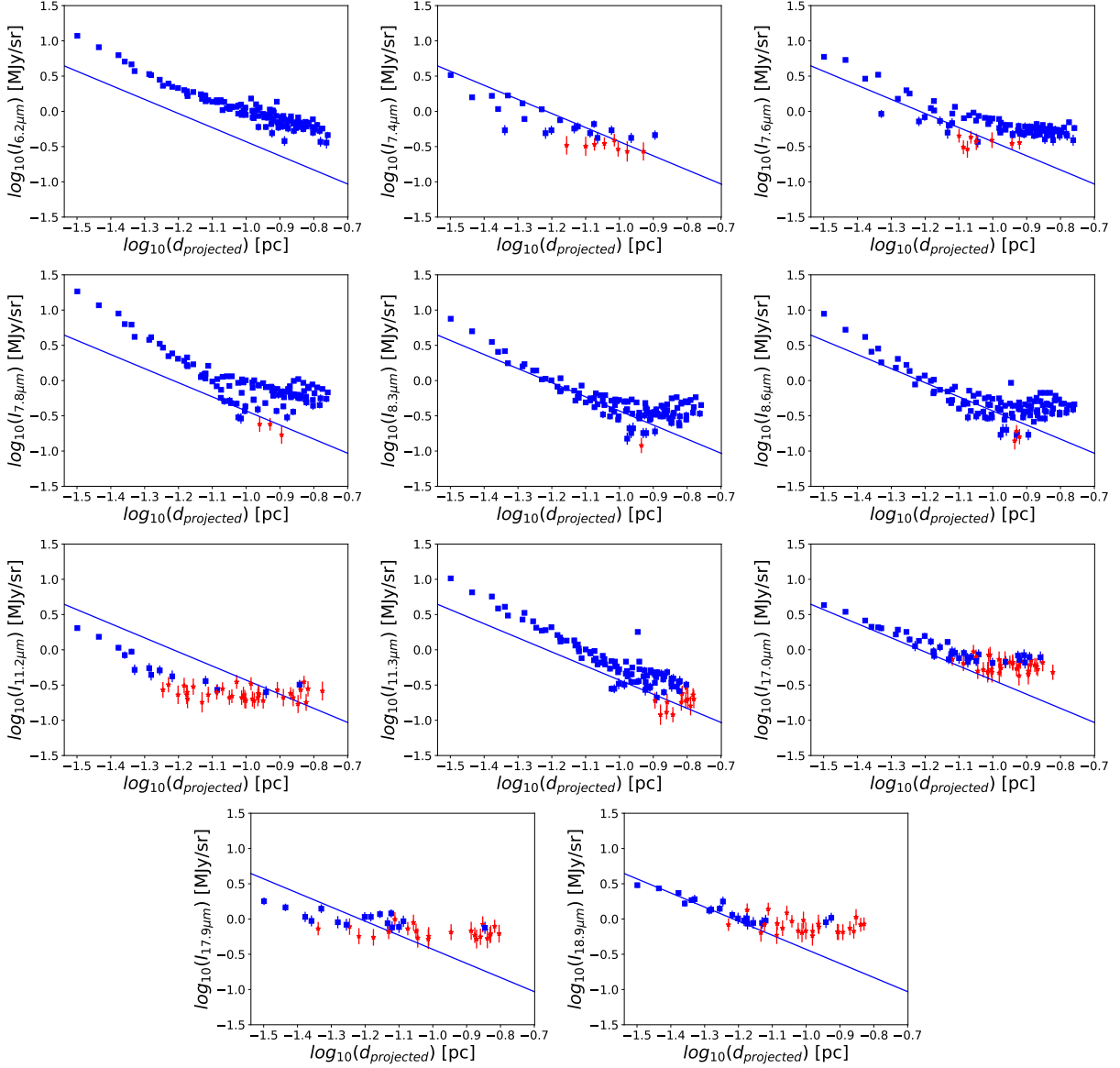


Figure 3.6: Logarithmic intensity of selected PAH features with respect to projected distance from the field star, HD 130079. Blue lines represent the inverse square scaling (with arbitrary normalization), to guide the eye. SN is marked in each by color and symbol with red stars marking the lowest, $3 < \text{SN} < 5$, and blue squares marking all data points with $\text{SN} > 5$.

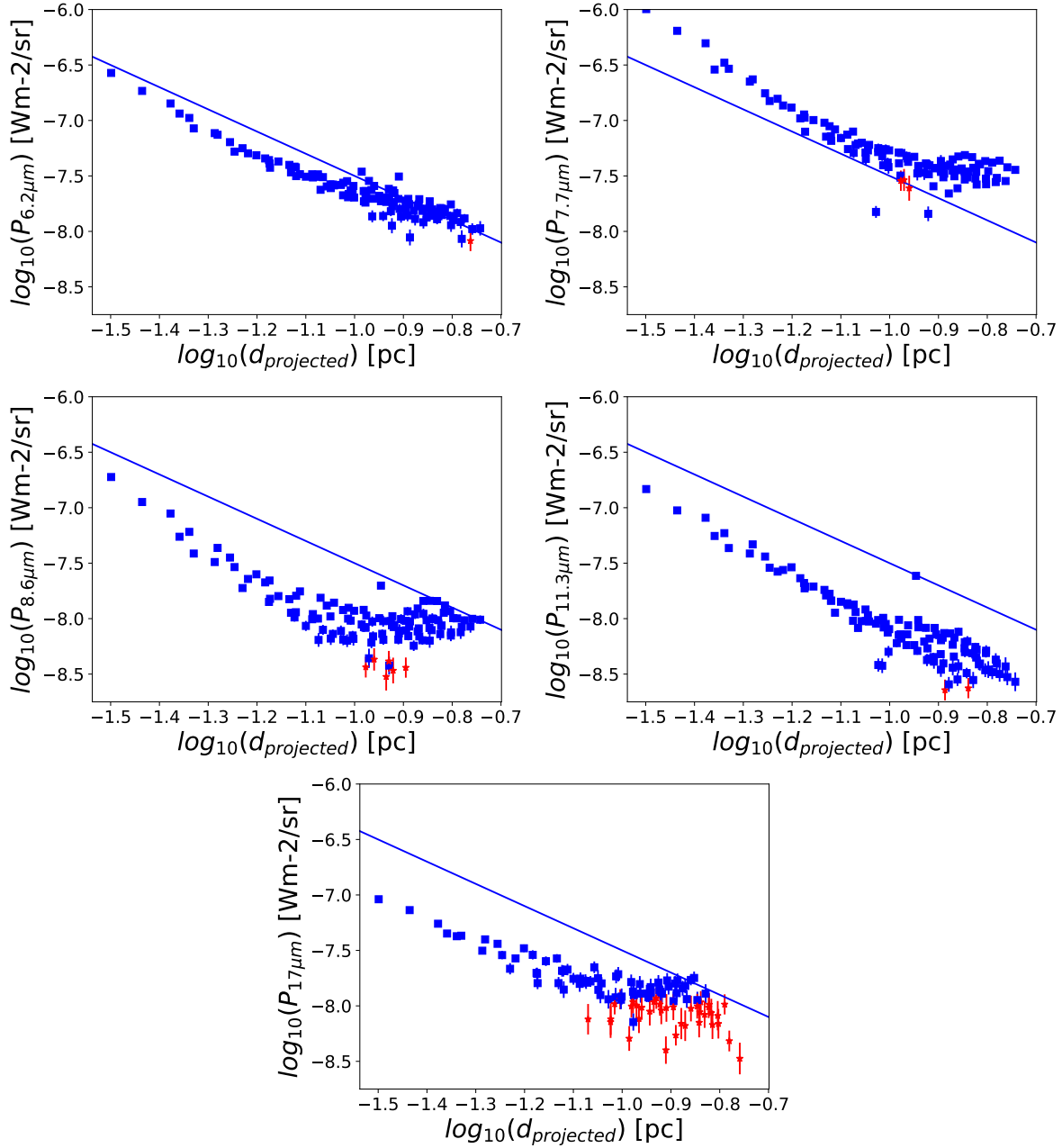


Figure 3.7: Logarithmic intensity of the integrated power of the main PAH features with respect to projected distance from the field star, HD 130079. Blue lines represent the inverse square scaling (with arbitrary normalization), to guide the eye. SN is marked in each by color and symbol with red stars marking the lowest, $3 < \text{SN} < 5$, and blue squares marking all data points with $\text{SN} > 5$.

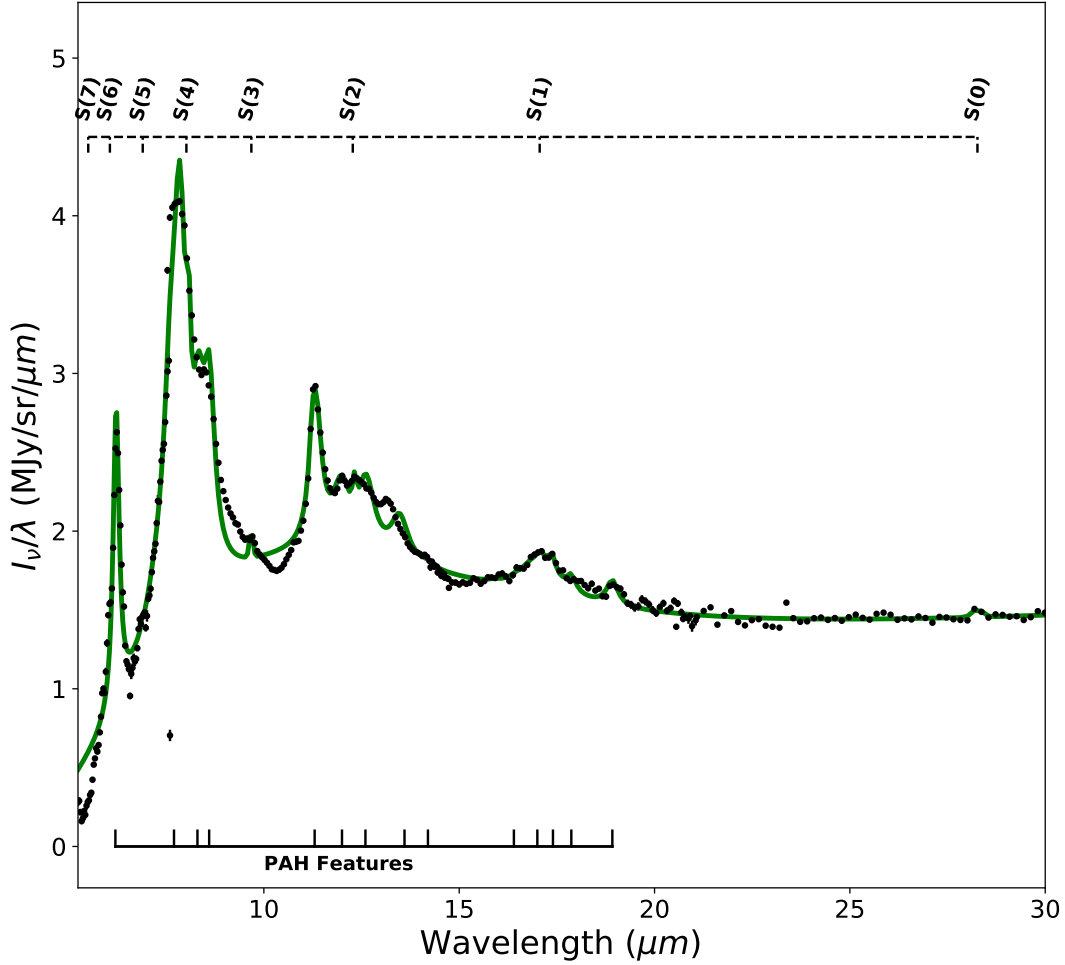


Figure 3.8: A zoom to the 5.5 – 30.0 μm segment of the spectrum for the region located at 0.03 pc projected distance from HD 130079 (see the upper panel in Figure 3.3), highlighting the region encompassing the majority of PAH activity. Green solid line indicates the fully fitted model extracted from PAHFIT (Smith et al., 2007b). Black points mark the real data points with error bars included. Dashed lines at the top of the plot mark the S(0-7) rotational lines of H_2 included in the PAHFIT fitting process, solid lines at the bottom of the plot indicate all of the PAH features included in the fitting process (within the 5.5 – 30.0 μm segment).

detailed zoom to the more narrow 5.75–6.75, 6.75–10.5, 10–15, and 15–20 μm segments of the spectrum for the same region, including model curves denoting various lines identified during the fitting procedure. The same decomposition was applied to all the analyzed 117 regions, and the results are given below in the following subsections.

5–7 Micron Features

In the upper left panel of Figure 3.9, the decomposition of the 6.2–6.3 μm feature is shown. Our system has a consistent peak wavelength across the 117 regions of 6.22 μm . [Peeters et al. \(2002\)](#) perform an investigation of the shift of the 6.3 μm PAH feature due to the addition of a nitrogen atom in the molecule. The 6.3 μm feature is represented by pure PAHs where as a shifted peak around 6.2 μm is emitted by substituted PAH species. Our observations are consistent with the findings presented in [Peeters et al. \(2002\)](#) for reflection nebulae, in which, it is suggested that the shifting of the peak wavelength is due to the presence of nitrogen in the observed PAH molecules.

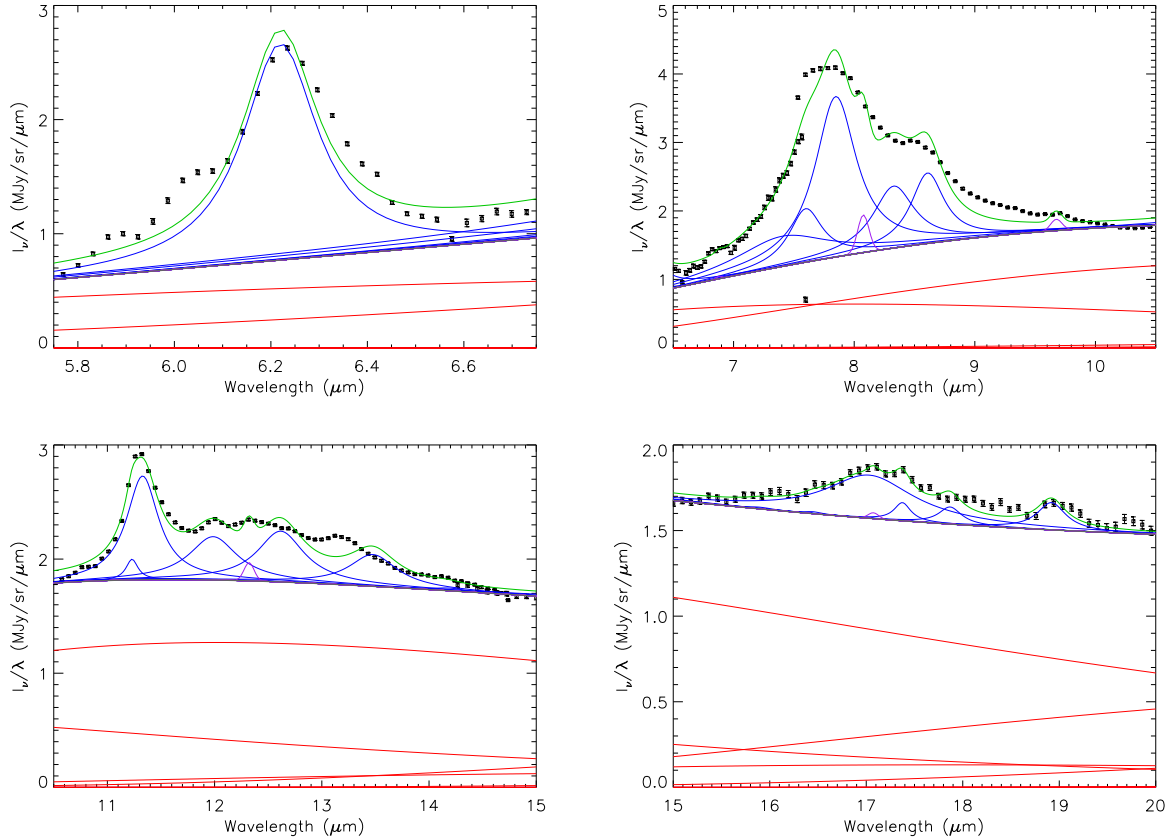


Figure 3.9: Zoom in of spectral fit for the region located at 0.03 pc projected distance from HD 130079 (see the upper panel in Figure 3.3, and also Figure 3.8). Lines and points are same as defined in Figure 3.3, with the green solid line representing the fully fitted model.

Another factor that can influence the positioning of the 6.2 peak, is the presence of ice absorption around $6\ \mu\text{m}$ from water ice. The ice features at $6\ \mu\text{m}$ can be confused when significant PAH features are present at 5.25, 5.7, 6.2, and $7.7\ \mu\text{m}$ (Peeters et al., 2002, and refs. therein). Indeed we see strong features at 6.2 and $7.7\ \mu\text{m}$ due to our PAH compounds, which makes it difficult to diagnose any potential ice absorption around $6\ \mu\text{m}$.

The lack of water ice in this spectral range is consistent with what is expected for the cloud. The observations indicate that the ice formation threshold occurs for A_V above 1.6 mag toward different regions (e.g., Whittet et al., 2001; Chiar et al., 2011; Boogert et al., 2013; Whittet et al., 2013). Nevertheless, the visual extinction at the edges of DC 314.8–5.1 is estimated to be equal to 1.08 ± 0.2 mag, without the foreground effect (Whittet, 2007). Other molecules that show strong IR absorption features at around $6\ \mu\text{m}$, such as HCOOH, H₂CO, and CH₃CHO, are more volatile than water, and thus would be formed in regions with larger extinction values ($A_V > 3$ mag).

7–10 Micron Features

The 7–10 μm spectral region is complex and is decomposed into several Drude profiles. The statistically significant and well defined PAH features in this spectral selection are the ones centered at 7.7 and $8.6\ \mu\text{m}$, as shown in Figure 3.9 upper right. The $7.7\ \mu\text{m}$ profile is fitted with three Drude profiles centered at 7.4, 7.6, and $7.8\ \mu\text{m}$. The peak of this feature is located longwards of $7.6\ \mu\text{m}$, which suggests a more dominant $7.8\ \mu\text{m}$ component. According to Peeters et al. (2002), this behaviour is common among reflection nebulae, which typically display, in addition, the shifted $6.2\ \mu\text{m}$ PAH feature, as is the case in DC 314.8–5.1 (see Section 3.5.2).

As discussed in Bregman & Temi (2005), PAHs in the diffuse ISM that have had long exposure to UV emission, are dominated by a $7.7\ \mu\text{m}$ emission feature with a peak around $7.6\ \mu\text{m}$. However, after integration into a cloud, these PAHs are chemically processed, and so the emission feature becomes shifted towards $7.8\ \mu\text{m}$, and then back toward $7.6\ \mu\text{m}$ only when having been exposed to an ionizing UV continuum in a reflection nebulae. The fact that, in the analyzed segment of DC 314.8–5.1, we see a dominant emission component centered near $7.8\ \mu\text{m}$, with a non-negligible contribution from the emission at $7.6\ \mu\text{m}$, implies therefore, that in addition to the “cloud-native”, chemically processed, PAH population, we also see a fraction of PAHs already being processed by the UV radiation of the neighbouring star, HD 130079.

10–15 Micron Features

A strong 11.2 – $11.3\ \mu\text{m}$ feature is commonly attributed to neutral PAHs within the cloud, and is correlated with many other PAH features. The profile in PAHFIT is comprised of two Drude profiles located at 11.2 and $11.3\ \mu\text{m}$. Figure 3.9 bottom left shows that the 11.2 and $11.3\ \mu\text{m}$ Drude profiles contribute to one PAH feature with a peak wavelength of ~ 11.25 , but with a significantly more dominant contribution from the $11.3\ \mu\text{m}$ profile, and a lesser contribution from the $11.2\ \mu\text{m}$

profile. As is visible in Figure 3.4, this feature is dominated by large primarily neutral PAHs with the red wing of the feature being contributed to by anion PAHs. The $11.3\ \mu\text{m}$ Drude profile follows the inverse power-law trend nicely, unlike the $11.2\ \mu\text{m}$ Drude profile. The overall integrated feature, however, does follow the power-law trend.

We note that PAHFIT does not fully converge in the $12 - 14\ \mu\text{m}$ region. Although the $12\ \mu\text{m}$ and $12.6\ \mu\text{m}$ PAH features are statistically significant, it is visible in Figure 3.9, that these lines are included in an attempt to fit the plateau present in this region and are not clear emission line detections. In Peeters et al. (2017), this plateau ($10 - 15\ \mu\text{m}$) is attributed to a blending of irregular, small, and clustered PAHs emitting from the C-H bending modes (single, duo, trio, and quartet H atoms; see Tielens, 2008; Peeters et al., 2017; Allamandola et al., 1989; Bregman et al., 1989, for an in-depth discussion of these plateau features). Due to PAHFIT not taking into account the plateau nature of this spectral section, we do not further consider the features between $12-14\ \mu\text{m}$, as we cannot be confident with these detections.

15–20 Micron Features

In the region past $15\ \mu\text{m}$, see Figure 3.9 lower right panel, PAHFIT takes into account six Drude profiles at 15.9 , 16.4 , 17.0 , 17.4 , 17.9 , and $18.9\ \mu\text{m}$ to fit the PAH features. The prominent (and as such statistically significant) features present here are the integrated PAH feature at $17.0\ \mu\text{m}$ as well as the PAH Drude profile at $18.9\ \mu\text{m}$.

3.5.3 Dust Continuum

The PAHFIT process allows for eight thermal dust continuum components (featureless modified blackbodies), at fixed temperatures in the range $35-300\ \text{K}$; the set of best-fit amplitudes of all the components is expected to closely represent a smooth distribution of grain temperatures within the source (Smith et al., 2007b). Based on the fits obtained for each region extracted from the Spitzer IRS mapping data for DC 314.8–5.1, we can investigate the dominance of the eight model dust continuum components fit, with respect to the distance from the star, see Figure 3.10. Data points with a $\text{SNR} < 3$ were excluded, which comprised many of the lower temperature components. SN was taken from the fitted profile and the respective error in that fit.

Firstly, we note that not all the dust continuum components are required by the fitting procedure in all the 117 regions analyzed. The prevalence of the dust components in the regions varies widely from $\sim 5\%$ (e.g., the $35\ \text{K}$ and $40\ \text{K}$ components), up to even $> 95\%$ in the case of the 200 , and $300\ \text{K}$ components. This indicates, that the continuum emission of the dust, with the provided model temperatures, requires a full mix of lower and higher temperature blackbodies in the majority of sampled regions for a comprehensive fit of the continuum emission, in agreement with the findings by Whittet (2007).

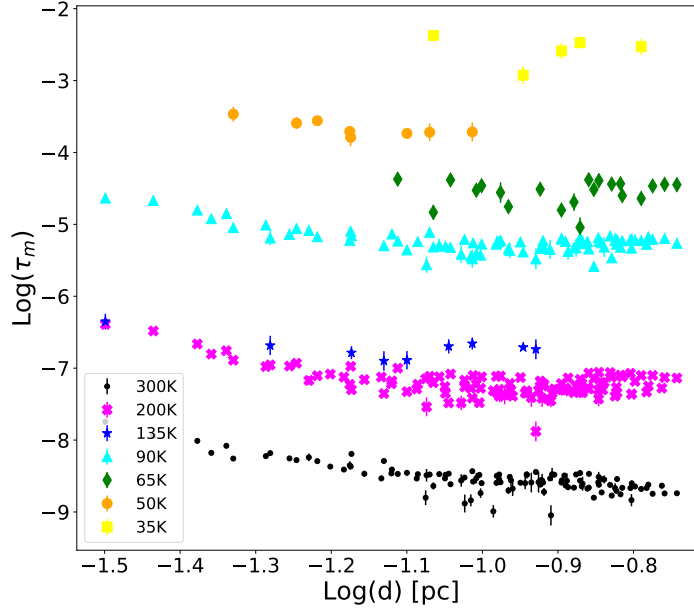


Figure 3.10: The relative strength of the dust continuum components with fixed model temperatures of 300, 200, 135, 90, 65, 50, 40, and 35 K, with increasing (projected) distance from the star HD 130079.

In Figure 3.10, we plot the extracted relative normalization values for each temperature bin, τ_m , as a function of the distance from the star. These relative normalizations are defined in PAHFIT through the equation for the dust continuum intensity

$$I_{\nu}^{(\text{dust})} = \sum_{m=1}^8 \tau_m \frac{B_{\nu}(T_m)}{(\lambda/\lambda_0)^2} \quad (3.1)$$

where B_{ν} is the blackbody function, T_m are the selected thermal dust continuum temperatures, and $\lambda_0 = 9.7 \mu\text{m}$ (Smith et al., 2007b). In the figure, each temperature bin is color coordinated with their respective points for the fit shown.

Studies have shown that quiescent, non-active, cores of dust clouds, have on average temperatures around 7–20 K, with colder temperatures dominating in the central regions (Bergin & Tafalla, 2007). Molecular clouds, on the other hand, maintain on average temperatures around 20–30 K (Ward-Thompson, 2002). In the case of DC 314.8–5.1, the most prominent dust continuum component corresponds to the temperature of 40 and 35 K, having orders of magnitude higher normalizations than the hotter counterparts. These are, however, the lowest temperature bins considered in PAHFIT, and no lower-temperature dust components are considered during the fitting because the dust below 35 K is too cold to make any contribution at $\lambda < 40 \mu\text{m}$ (Smith et al., 2007b).

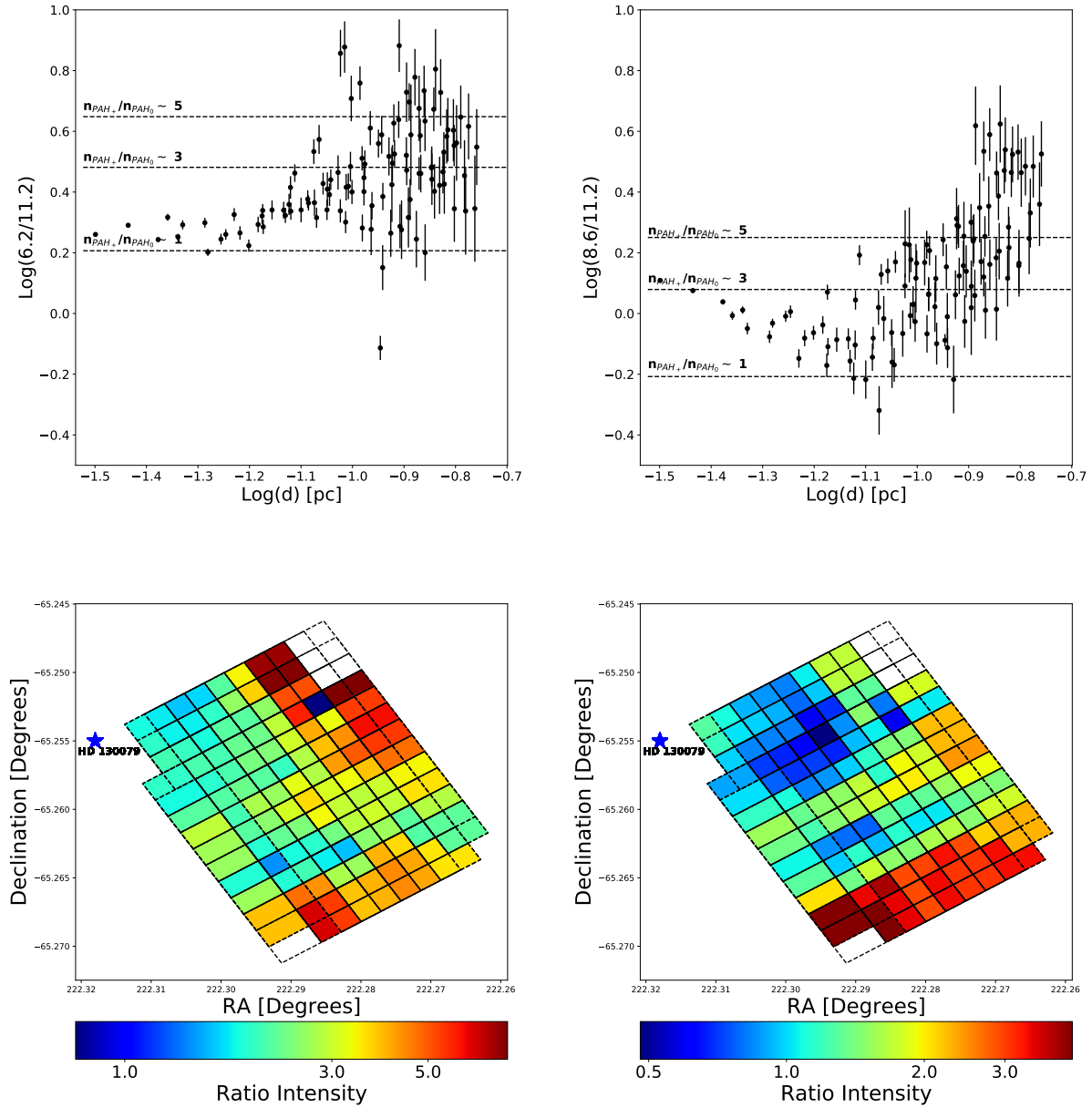


Figure 3.11: (top panels) Diagram showing the 6.2/11.2 intensity ratio (left) and 8.6/11.2 intensity ratio (right), based on the integrated profiles, versus the projected distance from HD 130079. Horizontal lines correspond to the intensity ratios expected for given values of the ionization parameter $n_{\text{PAH}^+}/n_{\text{PAH}_0}$, based on the best-fit correlations by [Boersma et al. \(2018\)](#), namely $I_{6.2\mu\text{m}}/I_{11.2\mu\text{m}} = 0.90 + 0.71 \times (n_{\text{PAH}^+}/n_{\text{PAH}_0})$, and $I_{8.6\mu\text{m}}/I_{11.2\mu\text{m}} = 0.33 + 0.29 \times (n_{\text{PAH}^+}/n_{\text{PAH}_0})$. (bottom panels) RA/DEC maps displaying the 6.2/11.2 intensity ratio (left) and 8.6/11.2 intensity ratio (right).

3.6 Discussions

3.6.1 PAH Ionized Fraction

Boersma et al. (2014) derived a relation between the number density ratio of PAH cations to neutrals, $n_{\text{PAH}^+}/n_{\text{PAH}0}$, and the main physical parameters in the system, including gas temperature T , ionizing radiation field G_0 , free electron number density n_e , and the PAH number of carbon atoms N_C , namely

$$\frac{n_{\text{PAH}^+}}{n_{\text{PAH}0}} \simeq 5.11 \times 10^{-6} N_C^{1/2} G_0 T^{1/2} n_e^{-1}, \quad (3.2)$$

where T is given in Kelvin, G_0 is in the Habing field units, and n_e is in cm^{-3} . Note that the PAH ionization parameter is often defined as $\chi \equiv G_0 T^{1/2} n_e^{-1}$, so that for the exemplary $N_C \simeq 50$ one has $(n_{\text{PAH}^+}/n_{\text{PAH}0}) \sim 0.37 (\chi/10^4)$.

For the rough estimates regarding the cation-to-neutral PAH ratio in DC 314.8–5.1 subjected to the ionizing photon field of HD 130079, we therefore made the following approximations. First, we assume the dominant gas temperature component of $T \sim 800$ K, according to the discussion by Boersma et al. (2018) for the photo-dissociation region (PDR) in NGC 7023. For the free electron number density, on the other hand, we follow the “diffuse ISM approximation”, stating that all free electrons come from CII with the abundance of 1.4×10^{-4} (see Boersma et al., 2018, and references therein). Furthermore, we assume a standard power-law density profile for the globule, $n_{\text{H}} \simeq n_0 \times (r/R)^{-1.3}$, where r is the distance from the cloud center, and $R = \sqrt{ab}$ is the effective radius of an elliptical cloud characterized by the major and minor semi-axes a and b , respectively. This, along with the values $2a \simeq 0.9$ pc, $2b \simeq 0.6$ pc, and the total mass of the cloud $\simeq 160 M_{\odot}$ (Whittet, 2007, corrected for the 435 pc distance), gives $n_0 \sim 7 \times 10^3 \text{ cm}^{-3}$, and hence $n_e \sim 0.75 \text{ cm}^{-3}$ around $r \sim 0.45$ pc $\gtrsim R$.

Finally, for estimating the ionizing photon field for HD 130079, we take a stellar temperature of $T_{\star} = 10,600$ K, radius $R_{\star} = 2.7 \times R_{\odot}$, and assume a blackbody emission spectrum for the starlight

$$B_{\nu} \propto \frac{\nu^3}{\exp\left(\frac{h\nu}{kT}\right) - 1}, \quad (3.3)$$

such that the total luminosity of the star is $L_{\star} = 4\pi R_{\star}^2 \sigma_{\text{SB}} T^4$. This gives the FUV luminosity of

$$L_{\text{FUV}} = f_{\text{FUV}} \times L_{\star} \simeq 3 \times 10^{34} \text{ erg s}^{-1}, \quad (3.4)$$

where the bolometric correction factor is

$$f_{\text{FUV}} \equiv \frac{\int_{\nu_1}^{\nu_2} d\nu B_{\nu}}{\int_0^{\infty} d\nu B_{\nu}} \simeq 0.1 \quad (3.5)$$

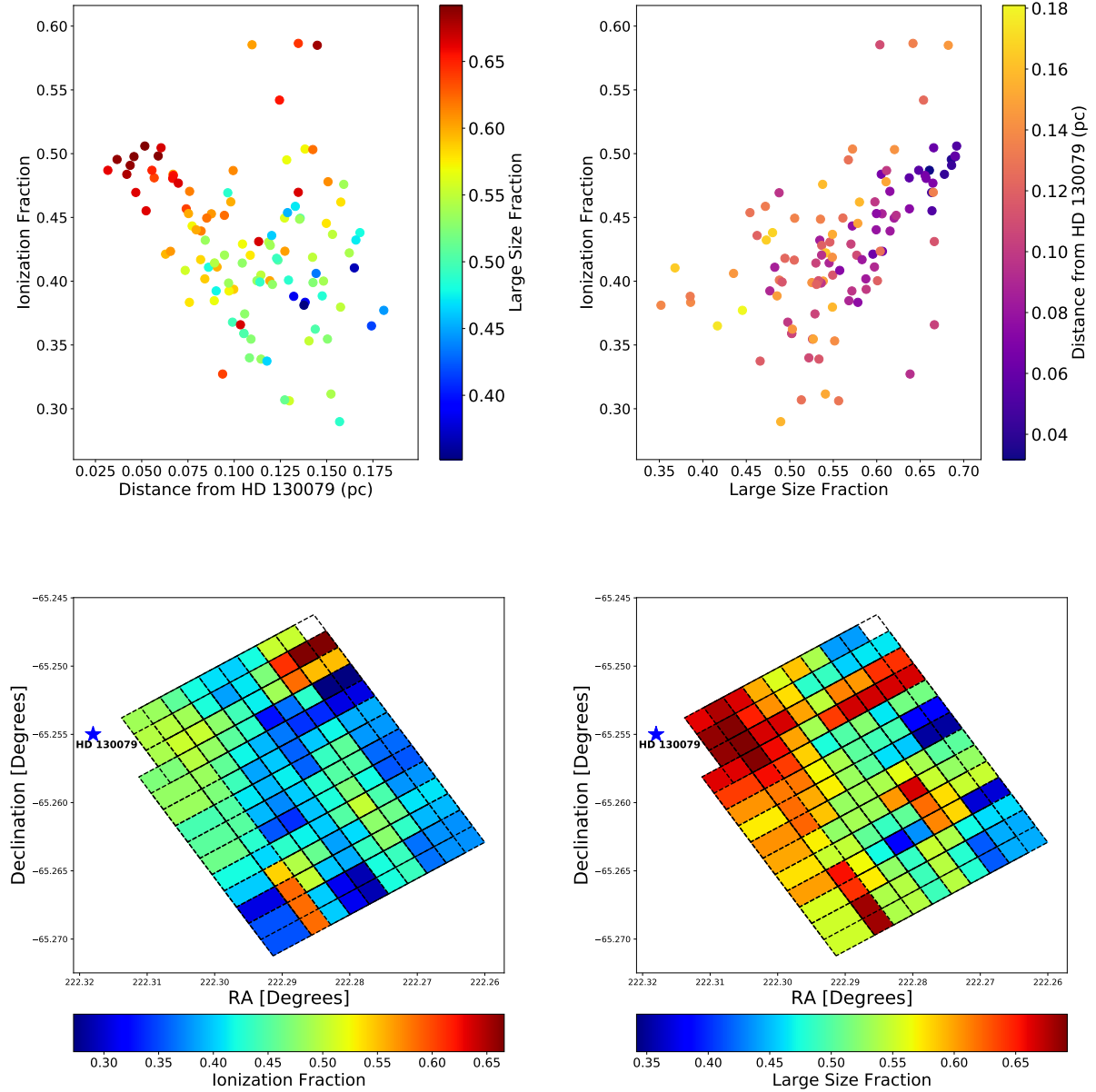


Figure 3.12: (top left panel) Pypahdb values for the ionization fraction vs. distance with color coding according to the large size fraction, where large molecules are defined as $N_C > 40$). (top right panel) Pypahdb values for the ionization fraction vs. large size fraction with color coding according to the distance from HD 130079. Data points included are those from regions with a $\text{SN} \geq 5$. (bottom) RA/DEC maps displaying the intensity of (left) the ionization fraction and (right) the large size fraction for the sampled regions.

with $h\nu_1 = 6\text{ eV}$ and $h\nu_2 = 13.6\text{ eV}$. Consequently, at a given distance from the star d , where the FUV flux of the star is $F_{\text{FUV}} = L_{\text{FUV}}/4\pi d^2$, the ionizing photon field in Habing units reads as

$$G_0 = \frac{F_{\text{FUV}}}{1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}} \sim 174 \quad (3.6)$$

for $d = 0.03\text{ pc}$, which is the distance to the nearest sampled region to the star in DC 314.8–5.1. We note that G_0 drops to ~ 4 at the most distant region analyzed, at a distance of $d \simeq 0.18\text{ pc}$ (with no extinction correction taken into account).

All the above estimates therefore imply $n_{\text{PAH}^+}/n_{\text{PAH}0} \sim 0.5$ around the region nearest to HD 130079 in DC 314.8–5.1 ($d = 0.03\text{ pc}$) for the general, illustrative, value of $N_C \sim 100$, and progressively smaller levels away from the photo-ionizing star, HD 130079. The resulting “outskirts level” value is, in fact, not far off from the PAH cations-to-neutrals ratio, $\gtrsim 1$, implied for the region by the observed 6.2/11.2 PAH intensity ratio, as well as the 8.6/11.2 line ratio, both considered by Boersma et al. (2018) to be good proxies for the ionized fraction parameter (see also Zang et al., 2019). However, the discrepancy between these values increases toward the globule’s central regions (up to $d = 0.18\text{ pc}$), for which the Equation 3.2 implies, formally, $n_{\text{PAH}^+}/n_{\text{PAH}0} < 0.01$, while the observed PAH intensity requires this ratio to be of the order of a few.

To illustrate the above-mentioned inconsistency, in Figure 3.11 we plot the 6.2/11.2 and 8.6/11.2 ratios (left and right columns respectively), as functions of distance from the star; in the top panels, we superimpose for illustration the lines corresponding to the intensity ratios expected for given values of the ionization parameter $n_{\text{PAH}^+}/n_{\text{PAH}0}$, based on the best-fit correlations by Boersma et al. (2018), namely $I_{6.2\mu\text{m}}/I_{11.2\mu\text{m}} = 0.90 + 0.71 \times (n_{\text{PAH}^+}/n_{\text{PAH}0})$, and $I_{8.6\mu\text{m}}/I_{11.2\mu\text{m}} = 0.33 + 0.29 \times (n_{\text{PAH}^+}/n_{\text{PAH}0})$.

As shown in Figure 3.11, both the 6.2/11.2 and 8.6/11.2 ratios, remain relatively high throughout the globule, revealing similar trends, with the values increasing somewhat toward the central regions of the cloud (however with significant spread of data points). With the Boersma et al. scaling relation, this would imply an overall high ionization $n_{\text{PAH}^+}/n_{\text{PAH}0} > 1$ within the entire reflection nebula.

The breakdown enabled by the pypahdb fitting, offers a direct view on the ionization fraction within DC 314.8–5.1. As shown in Figure 3.12, the ionized fraction returned by the fitting procedure, $n_{\text{PAH}^+}/(n_{\text{PAH}^+} + n_{\text{PAH}0})$, is $\simeq 0.5$ within the regions of the cloud closest to the ionizing star, and decreasing somewhat down to $0.3 - 0.4$ at further distances, again with an increasing spread. These values therefore correspond to a ratio $n_{\text{PAH}^+}/n_{\text{PAH}0} \simeq 1$ at the outskirts of the cloud, closer to the star, and down to $\sim 0.5 - 0.7$ at the furthest distances from the star probed in our analysis. Based on this, we therefore conclude that we do see an overall decrease in the ionization fraction with distance, which is however much more modest than expected based solely on the decrease in the ionizing continuum from the star, hinting at the potential role of alternative ionization factors at play, such as ionization due to cosmic-rays.

Interestingly, the pypahdb fitting also provides insight into the large size fraction of the PAH

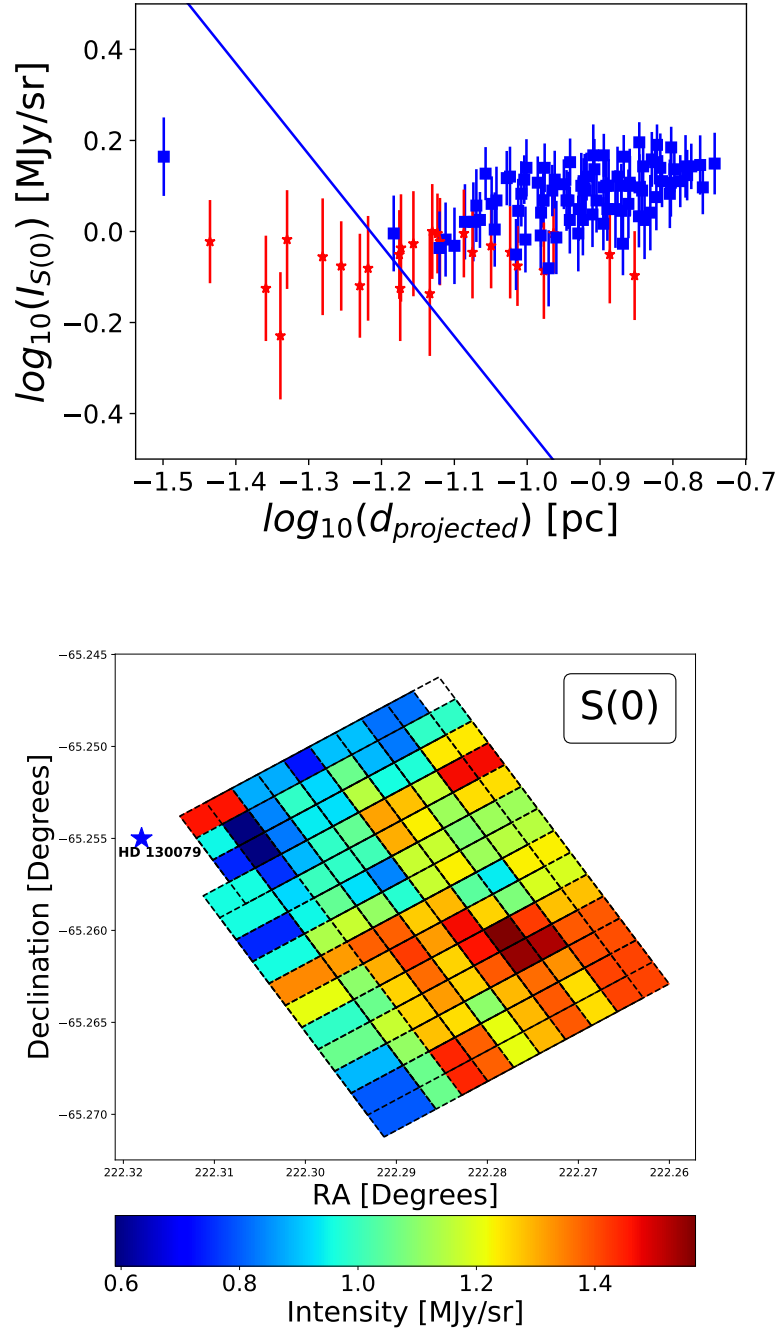


Figure 3.13: (top) Logarithmic intensity of the H₂ S(0) line located at 28.1 – 28.2 μm plotted with distance from the field star, HD 130079. The blue line represent the inverse square scaling (with arbitrary normalization), to guide the eye. SN is marked in each by color and symbol with red stars marking the lowest data points, $3 < \text{SN} < 5$, and blue squares marking all data points with $\text{SN} > 5$. (bottom) RA/DEC maps displaying the intensity of fitted H₂ S(0) line in each the sampled regions with a $\text{SN} > 3$.

molecules, where large molecules are defined as those with $N_C > 40$. The corresponding results are again shown in Figure 3.12, revealing that the PAH emission of the highly ionized regions at the cloud’s boundaries, is dominated by large molecules (large size fraction > 0.6), which become less prevalent for the regions closer to the center of the cloud (large size fraction < 0.6).

We furthermore perform a basic correlation study between the two parameters, ionization and large size fractions, over all of the sampled regions with a $SN \geq 5$, shown in the top right panel in Figure 3.12. We utilize both a Pearson’s product-moment correlation and Kendall’s rank correlation. We find a statistically significant correlation with both methods, showing a statistic of 0.56 and 0.45 and p-value of 1.2×10^{-10} and 3.6×10^{-12} for Pearson’s and Kendall’s respectively.

3.6.2 Molecular Hydrogen Detection

As shown in Figure 3.13, the H_2 S(0) line is detected in our system at high significance ($SN > 5$) only at larger distances from the star. On the other hand, its intensity remains fairly constant throughout those outer regions probed in our analysis.

The excitation for H_2 can occur through several processes, including inelastic collisions with gaseous species, radiative pumping from far-ultraviolet (FUV) radiation, or the formation process; the dominant source of the pure rotational line S(0) is collisional excitation, and as such the S(0) line intensity should be sensitive to the gas temperature at the PDR front (e.g., [Le Boulrot et al., 1999](#); [Neufeld & Yuan, 2008](#); [Habart et al., 2011](#)). The H_2 excitation may however also result from interactions with secondary electrons generated by cosmic rays penetrating and ionizing the cloud ([Wakelam et al., 2017](#)).

3.7 Conclusions & Final Remarks

In this paper, we have discussed the MIR spectroscopic properties, provided by the IRS instrument on the Spitzer Space Telescope, of the quiescent dark cloud, DC 314.8–5.1. This study has focused on the lower-resolution MIR spectra in the range of 5–35 μm . Spectra were extracted from 117 overlapping spatial regions over ≈ 0.18 pc spanning the reflection nebula induced by the field star, HD 130079. Spectral fitting revealed a plethora of PAH features, the inspection of which led to the following conclusions:

1. The intensities of PAH features generally decrease over distance from the ionizing star toward the cloud center, some however showing a saturation (plateau) in the intensity profiles at larger distances.
2. The relative intensities of both the 6.2 and 8.6 features with respect to the 11.2 μm feature remain high throughout the globule, suggesting a relatively large cation-to-neutral PAH

ratio $\gtrsim 1$; this value is consistent with the expected ionization level in the vicinity of the illuminating star, where the estimated ionization parameter $\chi \sim 10^4$; however, for the cloud's more central regions, where χ drops to ~ 100 , a discrepancy emerges between the expected value and the one implied by the observed PAH intensity ratio.

3. The performed pypahdb fitting, confirms a high ionized fraction within the cloud, ranging from $\simeq 0.5$ within the regions in the closest vicinity to the ionizing star, down to $\sim 0.3 - 0.4$ at larger distances. Moreover, the PAH emission of the highly ionized regions at the cloud's boundaries, appears to be dominated by large molecules, which become less prevalent for the regions closer to the center of the cloud.
4. The investigation of the $7.7 \mu\text{m}$ profile in the reflection nebula of DC 314.8–5.1 suggests that, in addition to the chemically processed PAH population of the cloud, we also see a fraction of PAHs UV-processed by the neighbouring star, HD 130079.
5. We detected the $\text{H}_2 \text{S}(0)$ line at $28.1 - 28.2 \mu\text{m}$ with a higher significance at further distances from the star.

All in all, our results hint at divergent physical conditions within the quiescent cloud DC 314.8–5.1 as compared to molecular clouds with ongoing starformation, and may suggest a role played by cosmic-rays in the ionization of the system.

Acknowledgements

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This work has made use of data from the European Space Agency (ESA) mission Gaia (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. We are grateful to Timo Prusti for advice on Gaia data.

Chapter 4

Multiwavelength Survey of Dark Globule DC 314.8–5.1: Point Source Identification and Diffuse Emission Characterization

This chapter originally appeared as ‘Multiwavelength Survey of Dark Globule DC 314.8–5.1: Point Source Identification and Diffuse Emission Characterization’ by E. Kosmaczewski et al. 2022, arXiv:2209.02372, submitted for publication to The Astrophysical Journal on September 6, 2022 ([Kosmaczewski et al., 2022a](#))

Abstract

We present an analysis of the multi-wavelength observations of the dark globule, DC 314.8–5.1, using the optical survey Gaia, the near-infrared survey 2MASS, mid-infrared survey WISE along with dedicated imaging with the Spitzer Space Telescope, and finally X-ray data obtained with the Swift-XRT telescope. The main goal of this analysis was to identify possible pre-main sequence stars and young stellar objects (YSOs) associated with the globule. For this purpose, we studied the infrared colors of all point sources coinciding within the boundaries of the cloud, as inferred from the optical extinction maps. After removing the sources with spectra of non-stellar types, we investigated the Gaia parallaxes for the YSO candidates, finding that none of them are physically related to DC 314.8–5.1. In addition, we probed the presence of pre-main sequence stars lacking infrared counterparts with Swift-XRT, and found no candidates down to a luminosity level $\lesssim 10^{31} \text{ erg cm}^{-1}$ in the 0.5–10 keV range. Our detailed inspection of the gathered data confirm a very young, “pre-stellar core” evolutionary stage of the cloud. As such, DC 314.8–5.1 constitutes a compact reservoir of cold dust and gas, enabling for a truly unique insight into a primordial form of the interstellar medium. Based on the archival Planck and IRAS data, we identify the presence of a hot dust, with temperatures reaching even up to 200 K, in addition to the dominant dust component at 14 K. Finally, we comment on the mass estimates for the globule.

4.1 Introduction

Dark clouds also called dark globules, provide crucial insight into the formation history of our Galaxy, the Milky Way, and in particular, into the physical and chemical structure of the interstellar medium (ISM) prior to the formation of stars. Only at later evolutionary stages do they become nurseries for protostars, but prior to that they constitute a dense and compact reservoir of a cold primordial form of the ISM (Ward-Thompson, 2002). From an observational point of view, we can study such structures through a detailed investigation of multi-wavelength data, as the cold dust and gas embedded in dark clouds do interact, at least to some extent, with the optical and UV emission of nearby stars, as well as with Galactic cosmic rays. At early evolutionary stages, the dim nature of dark clouds, makes this observational task rather difficult, often preventing truly comprehensive studies and, as such, a deeper understanding of these systems. Indeed much of the study of molecular clouds within the Galaxy has been focused on later evolutionary stages, specifically when stars have already formed and thus “polluting” the system with their radiation and outflows (Bergin & Tafalla, 2007). This process, however, is destructive and permanently alters not only the structure but the chemistry of a cloud and as such destroys any information about its original composition.

Here, we analyze the available archival data, and also the newly acquired data, for the source DC 314.8–5.1, originally classified in the Hartley et al. (1986) catalog as a compact dark globule at $b = -5$ degrees. The target has a serendipitous association with a field star, which illuminates a reflection nebula in the cloud. Basic physical properties of the system were discussed in Whittet (2007), who concluded — based on the Infrared Astronomical Satellite (IRAS) and the Two Micron All Sky Survey (2MASS) data — that the cloud is at the onset of low-mass star formation.

In our previous work on DC 314.8–5.1 (Kosmaczewski et al., 2022b), we performed an analysis of the mid-infrared spectra, obtained from the Spitzer Space Telescope, focusing on the polycyclic aromatic hydrocarbon (PAH) emission features which are prevalent throughout the mid-infrared range in the reflection nebula. Our studies revealed a surprisingly large cation-to-neutral PAH ratio, which could be explained by lower-energy cosmic rays (CRs) ionizing the cloud’s interiors, in addition to photo-ionization by the neighbouring star. While lower-energy CRs provide excess ionization in the globule, the higher-energy CRs should, at the same time, produce high-energy neutrinos and γ -rays, through the decay of charged and neutral pions following from inelastic CR collisions with the cold gas of the cloud (e.g., Bamba et al., 2009; Gabici, 2013; Padovani et al., 2020; Fujita et al., 2021). In fact, a low-significant γ -ray source coinciding with DC 314.8–5.1 was found in the analysis of the Fermi Large Area Telescope (LAT) data by Ackermann et al. (2018).

The main goals of the multi-wavelength data analysis presented here, are (i) the inspection of the archival Spitzer Space Telescope and Wide-field Infrared Survey Explorer (WISE) mid-infrared data, 2MASS near-infrared data, as well as Gaia optical data for point sources coinciding with the globule, to identify YSO candidates, and in this way to confirm an early evolutionary stage of

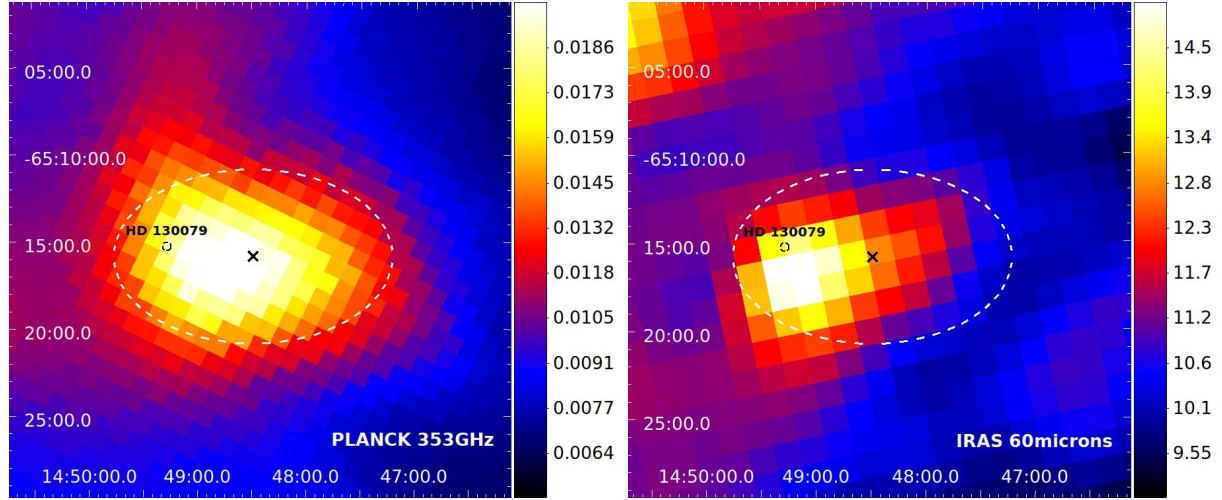


Figure 4.1: DC 314.8–5.1 at low-resolution maps from the Planck survey at 353 GHz with a linear scale from 0.005–0.02 kCMB (thermodynamic temperature) and IRAS survey at 60 μm with a linear scale from 9–15 MJy/sr (left, and right panel, respectively). The white dashed ellipse denotes the position of the globule with the central positioning based on the so-called “optical center” at RA(J2000) = 14h 48m 29.00s and Dec(J2000) = $-65^\circ 15' 54.0''$ marked by a black x, with an extent of $\sim 8' \times 5'$ following from [Kosmaczewski et al. \(2022b\)](#). The star, HD 130079, is marked in black in the eastern region of the cloud. The orientation of the image is such that North is directed upwards and East to the left.

the cloud, prior to the onset of star formation; (ii) the analysis of the newly acquired X-ray data from the Neil Gehrels Swift Observatory, allowing us to clarify the presence of pre-main sequence stars (PMSs) with no optical/infrared counterpart, hinted by the low-significant ROSAT source coinciding with DC 314.8–5.1, (iii) the characterization of the diffuse emission at microwave and infrared frequencies with low-resolution Planck and IRAS data.

4.2 Multi-wavelength Overview

DC 314.8–5.1 is a dark globule located approximately 5 degrees below the Galactic Plane in the southern constellation of Circinus, centered at an equatorial position of RA(J2000) = 14h 48m 29.00s and Dec(J2000) = $-65^\circ 15' 54.0''$. The globule is associated with a typical main sequence B9 V field star, HD 130079, present at the cloud’s eastern boundary, and illuminating a reflection nebula within the cloud ([Whittet, 2007](#)). The association of HD 130079 with DC 314.8–5.1 was established in [van den Bergh & Herbst \(1975\)](#) who identified the presence of reflection nebula utilizing the Palomar two-color survey of the southern sky, and further characterized the host clouds through the Absorption around the reflection nebulae determined from the density of field stars method. The parallax value for this star in the Gaia Early Data Release 3 (EDR3; [Gaia Collaboration et al., 2021](#)), is 2.2981 ± 0.0194 mas, corresponding to a distance of 435 ± 4 pc. [Bailer-Jones](#)

et al. (2021) determined both the geometric and photogeometric distances to the sources in the EDR3 catalog taking into respect extinction and utilizing a probabilistic approach based on a constructed three-dimensional model of our Galaxy; the geometric distance to the star HD 130079 is $431.7^{+3.2}_{-4.3}$ pc. Accordingly, the angular dimensions of the dark cloud $\sim 8' \times 5'$, originally constrained in Whittet (2007) based on the opacity in the visual image, translates to a projected linear size of $0.9 \text{ pc} \times 0.6 \text{ pc}$. The extinction characteristics through the cloud imply its mean hydrogen core number density $\sim 10^4 \text{ cm}^{-3}$, and the total mass $\sim 160 M_{\odot}$ (see Hetem et al., 1988; Whittet, 2007).

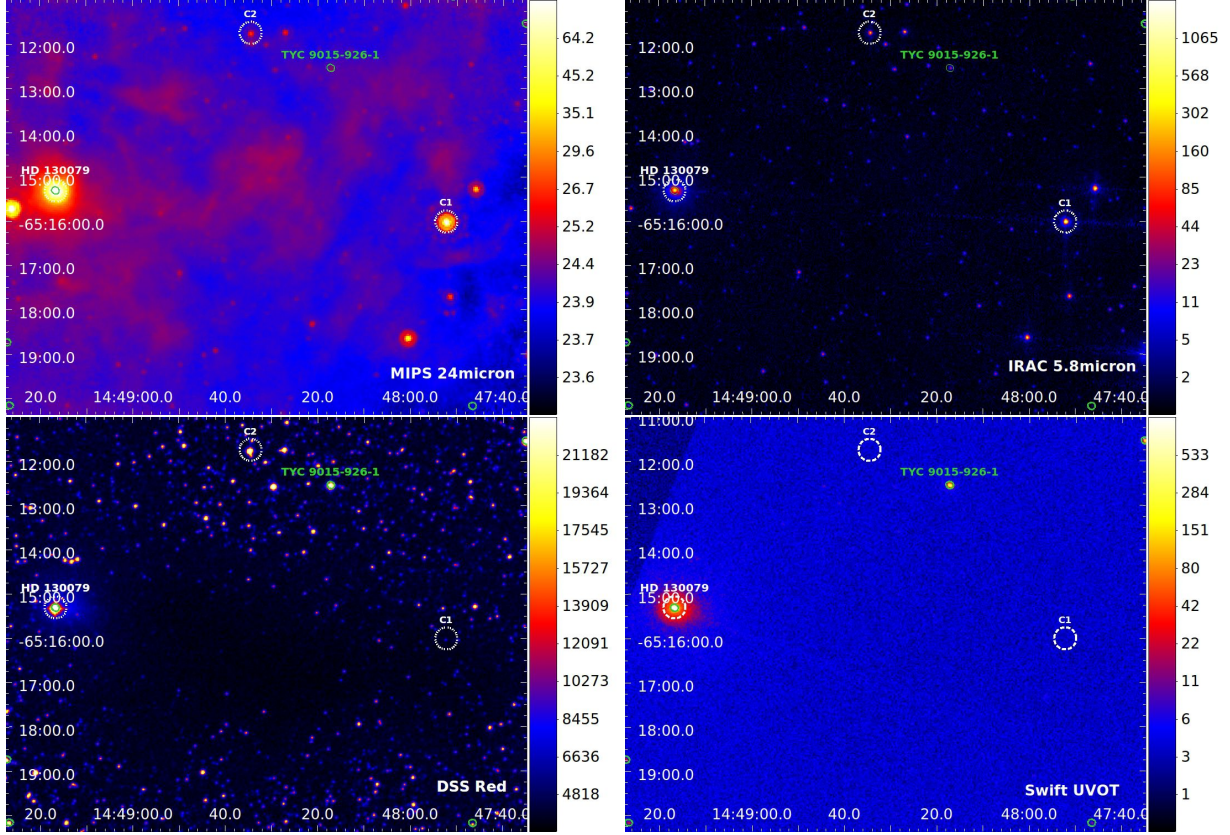


Figure 4.2: DC 314.8–5.1 region images from: **Top** (left) Spitzer MIPS $24 \mu\text{m}$ mosaic map where the colorbar indicates the log intensity scale from 23.5–100 MJy/sr; (right) Spitzer IRAC $5.8 \mu\text{m}$ where the colorbar indicates the log intensity scale from 0–2000 MJy/sr; **Bottom:** (left) DSS red image (700 nm) where the colorbar indicates the linear intensity scale from 3000–23000 cts (right) Swift UVOT M2–2250 Å band image of the same region. Colorbar indicates the log intensity scale from 0–1000 cts. Green circles and ellipses mark the UVOT detected sources. HD 130079 field star is marked in the left of the image, C1 marks the YSO candidate identified by Whittet (2007), C2 marks the YSO candidate identified in this work, TYC 9015-926-1 is marked in the northern boundary of the cloud, and S with a $6''$ radius marks the X-ray source detected with Swift-XRT.

4.2.1 Archival Low-Resolution Data

Planck

DC 314.8–5.1 is a fairly strong source of microwave emission, listed in the Planck Catalogue of Galactic Cold Clumps (PGCC; [Planck Collaboration et al., 2016c](#)) as PGCC G314.77–5.14. Modeling the cloud size on the Planck 857 GHz cold residual map with an elliptical Gaussian, returns FWHMs along the major and minor axes of $8'.36 \pm 0.34$ and $4'.60 \pm 0.19$, respectively. Fitting the modified black body $F_\nu \propto B_\nu(T) \times (\nu/\nu_0)^\beta$ to the Planck spectrum of the system, implies the gas temperature of $T = 14 \pm 1$ K, and the spectral index $\beta = 1.8 \pm 0.2$. The [Planck Collaboration et al.](#) estimate on the distance to DC 314.8–5.1, following from near-infrared extinction, is 400 ± 370 pc; when combined with the Planck photometry, the resulting mass estimate for the cloud, and its mean density, are $10 \pm 14 M_\odot$ and $892 \pm 544 \text{ cm}^{-3}$, respectively, which, even though basically unconstrained due to the large uncertainty in the Planck distance estimate, are both below the corresponding estimates by [Hetem et al. \(1988\)](#) and [Whittet \(2007\)](#).

The upper panel of Figure 4.1 presents the Planck map of the DC 314.8–5.1 region at 353 GHz; the central positioning of the system, based on the Planck morphology fitting, is offset by $1'.4$ to the east from the nominal positioning of DC 314.8–5.1, as stated in ([Otrupcek et al., 2000](#)) based on the CO $J = 1 - 0$ emission. This offset is most likely due to the emission from the field star, HD 130079, heating the dust in its vicinity and therefore shifting the peak of emission toward the eastern portion of the cloud.

IRAS

The far-infrared counterpart of DC 314.8–5.1 is a bright IRAS point source IRAS 14451–6502 in the IRAS point source catalog v2.0 ([Hetem et al., 1988](#); [Bourke et al., 1995](#); [Whittet, 2007](#)). IRAS contains fluxes in four bands, specifically, $12 \mu\text{m}$, $25 \mu\text{m}$, $60 \mu\text{m}$, and $100 \mu\text{m}$ tabulated in the HEASARC archival service. DC 314.8–5.1 is detected in all four bands with the lowest signal-to-noise (SN) of 5.1 for the $12 \mu\text{m}$ band and up to a SN of 26.1 for the $60 \mu\text{m}$ band with a SN of 15.8 and 8.8 for $25 \mu\text{m}$ and $100 \mu\text{m}$ respectively.

The lower panel of Figure 4.1 presents the IRAS map of the DC 314.8–5.1 region at $60 \mu\text{m}$; as follows, the far-infrared peak intensity is shifted to the east from the central positioning of DC 314.8–5.1 by $\sim 3'.5$.

ROSAT

A weak X-ray counterpart of DC 314.8–5.1 is present in the Second ROSAT all-sky survey (2RXS) source catalog ([Boller et al., 2016](#)), suggesting that DC 314.8–5.1 could be a source of X-ray photons. The position of the ROSAT J144833.7–651738, is nominally $1'.8$ offset to the south

from the central position of DC 314.8–5.1 (see Figure 4.11 in Appendix 4.6.2), but still contained within the cloud’s spatial range. The very low photon statistics, with the estimated ROSAT PSPC 0.1 – 2.4 keV count rate of $0.0175 \pm 0.0082 \text{ cts s}^{-1}$, corresponding to $8 \pm 4 \text{ cts}$, is insufficient for any spectral modeling of the signal.

4.2.2 High-Resolution Data

Spitzer

The Spitzer Space Telescope observational data for this work were acquired with the InfraRed Spectrograph (IRS; Houck et al., 2004), the Infrared Array Camera (IRAC; Fazio et al., 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al., 2004) imaging mode (Proposal ID 50039; P.I.: D. Whittet). In total, DC 314.8–5.1 was observed for a total of 6 hours in October of 2008 in five infrared bands: 3.6, 4.5, 5.8, and $8.0 \mu\text{m}$ with IRAC, and $24 \mu\text{m}$ with MIPS, with an angular resolution of $2''$ and $6''$ for IRAC and MIPS, respectively.

Spitzer imaging maps were obtained in all four IRAC bands. Due to the presence of many bright sources within our maps, we perform artifact correction utilizing the IRAC artifact mitigation tool, by following a procedure similar to that in the Spitzer Data Cookbook¹, and additional tools listed within, to produce mosaic maps in each band. The resulting $5.8 \mu\text{m}$ IRAC image is shown in the upper right panel of Figure 4.2, while all the four IRAC images are given in Appendix 4.6.1, Figure 4.9.

The reduction of the MIPS data products was performed following the recipe 22 in the Spitzer Data Cookbook using MOPEX (Makovoz et al., 2005). The MIPS $24 \mu\text{m}$ image of the DC 314.8–5.1 region, is shown in the left upper panel of Figure 4.2.

IRS stare observations were obtained in the SH mode centered on the field star, HD 130079. IRS stare observations were taken in the SH mode covering 9.9 to $19.6 \mu\text{m}$. Observations have a $S/N > 50$ due to the brightness of the source with an exposure time of 500s . IRS stare observational data for HD 130079 were reduced using a procedure similar to the recipe 17 outlined in the Spitzer Data Cookbook and the tools listed within (see footnote above). The reduction process included cleaning the pbcd products with IRSCLEAN, adding and averaging the products together with COAD, and fitting the profile and extracting spectra using SPICE. Default settings were used.

¹<https://irsa.ipac.caltech.edu/data/SPITZER/docs/>

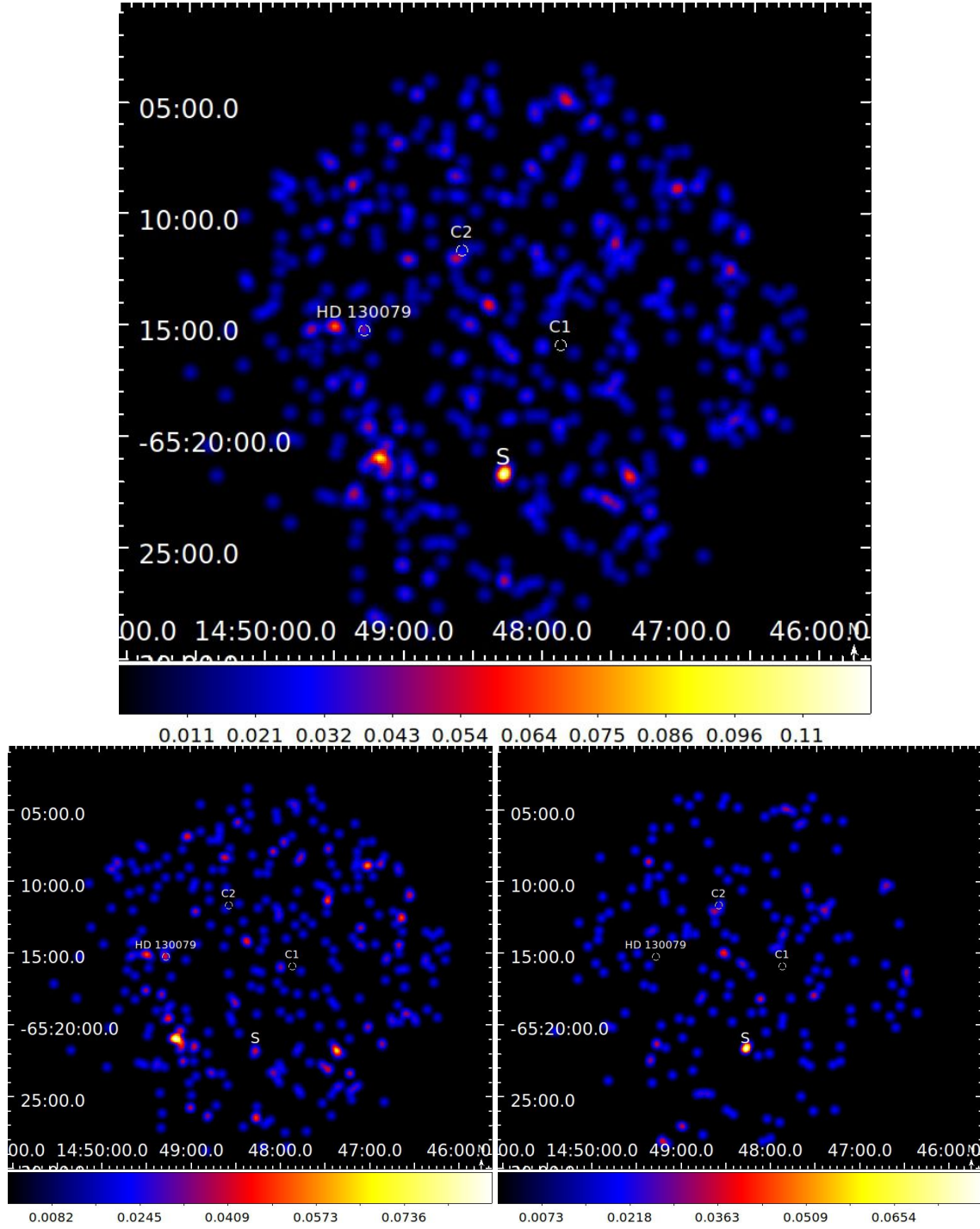


Figure 4.3: **Top:** Full-band 0.3–10 keV Swift XRT image of the DC 314.8–5.1 region, smoothed with a gaussian of radius 6 with a block parameter of 2. HD 130079 field star is marked in the left of the image, C1 marks the YSO candidate identified by [Whittet \(2007\)](#), C2 marks the YSO candidate identified in this work, and S marks the detected X-ray source. Colorbar indicates the log intensity scale in photons. **Bottom:** (left) Soft-band 0.3–2.0 keV and (right) hard-band 2–10 keV images of the same region.

WISE

WISE is an all-sky survey mission covering the entirety of the northern and southern hemispheres. The telescope obtains measurements in four bands (W1–W4) centered at 3.4, 4.6, 12, and 22 μm , with the corresponding resolution of 6".1, 6".4, 6".5, and 12", respectively (Wright et al., 2010). We obtained images in each band through the NASA/IPAC Infrared Science Archive (IRSA)² for the AllWISE Source Catalog. In addition, we queried all point sources within the extent of the cloud detected by WISE, the criteria for this selection are further discussed in Section 4.3.2. The WISE images of the DC 314.8–5.1 region are shown in Appendix 4.6.1, Figure 4.10.

DSS

The DC 314.8–5.1 spatial extension has been constrained in Whittet (2007) based on the opacity in the Digitized Sky Survey (DSS) image, see Figure 4.2, lower left panel. We note that the cloud core extinction according to Whittet is $\gtrsim 8.5$ mag.

Swift XRT & UVOT

Swift ToO observations of DC 314.8–5.1 were obtained with the Swift X-Ray Telescope (XRT) instrument (Burrows et al., 2000), as well as the UVOT (Roming et al., 2005) filter of the day, in this instance the UVM2–2250Å band (Proposal ID: 16282, Requester: E. Kosmaczewski). The target was observed for 3 ks on September 26, 2021. Swift XRT observations were taken in photon counting mode. Swift XRT images were produced utilizing the Swift XRT data products generator and as such three images were created: the entire spectral range from 0.3–10 keV, the soft band from 0.3–2.0 keV, and the hard band from 2–10 keV, with the procedure for image creation following from Evans et al. (2020).

The resulting UVOT M2–2250Å band image of the DC 314.8–5.1 region is shown in the lower right panel of Figure 4.2. The XRT maps of the cloud are given in Figure 4.3, including the full-band image, 0.3–10 keV (top panel), the soft-band image, 0.3–2.0 keV (bottom-left), and the hard-band image, 2–10 keV (bottom-right).

Source detection was performed for each of the three 2SXPS energy bands (i.e., 0.3–1.0 keV, 1–2 keV, 2–10 keV), as well as for the total energy range, following Evans et al. (2020). No sources were found for the individual 2SXPS energy bands, however, one weak source was detected within the total energy range, denoted hereafter as “S”. The source S is located at RA(J2000) = 14h 48m 16.72s and Dec(J2000) = $-65^\circ 21' 45''.6$, i.e. at the periphery or even outside of the cloud, with a good position error of 6".9, and the off-axis angle of 5'.8. The source was detected with

²<https://irsa.ipac.caltech.edu/frontpage/>

8 cts; with a background of ~ 0.5 cts, this resulted in a detection with a signal-to-noise of ~ 1.63 at a rate of $4.1_{-1.4}^{+1.8} \times 10^{-3}$ cts s $^{-1}$. The fact that the feature S is clearly visible in the hard-band image but not soft-band image (see bottom panels in Figure 4.3), indicates a hard X-ray spectrum of the source.

The Swift UVOT source extraction was performed utilizing the standard “uvotdetect” routine. We detected a total of 38 sources with a detection threshold of 5σ , see the left panel of Figure 4.2. Only two sources are detected within the extent of the cloud with the first (and brightest) being the field star HD 130079. The second source is a star, TYC 9015-926-1, in the northern region of the cloud at RA: 14h48m 17.134s, DEC: $-65^\circ 12' 33.051''$ with a Gaia measured parallax of 2.167 ± 0.0147 mas corresponding to a distance range of 458.36 – 464.62 pc, therefore making this object a (somewhat) nearby star located behind the cloud.

The comparison with the ROSAT archival data, visualized in Figure 4.11 of Appendix 4.6.2, indicates that the ROSAT low-significant detection is not confirmed by Swift XRT observations, but instead represents either an artifact of the 2RXS analysis, or a background transient/variable source. In the Discussion Section 4.4, we comment on it in more detail.

4.3 Identification of YSOs

Previous studies of DC 314.8–5.1 indicated that this system is in an early evolutionary state, prior to the onset of star formation (Whittet, 2007; Kosmaczewski et al., 2022b). Whittet (2007) performed a 2MASS survey of the region to identify potential YSOs, and found only two candidates out of a sample of 387 sources; one of those was excluded as an old star with significant dust reddening, the other one remained a viable YSO candidate, hereafter referred to as “C1”. In Kosmaczewski et al. (2022b), we showed a presence of divergent conditions from reflection nebula induced by star formation, suggesting that DC 314.8–5.1 is indeed at an early evolutionary stage, with no active star formation. However, to confirm this statement, one must perform a more in depth stellar search. Below, we expand on the YSO identification in the system, utilizing the data obtained from Spitzer IRAC, as well as the WISE, 2MASS, and Gaia surveys.

YSO candidates can be divided into three main classes, I–III (Lada, 1987). Class I sources are deeply-embedded protostars with infalling, dense envelopes, characterized by a rising or flat mid-infrared spectrum. Class II denoting YSOs that are pre-Main Sequence Stars with gas-rich optically-thick disks and on-going accretion onto the central star, and a decreasing MIR spectrum. Finally, Class III YSOs have gas-poor disks and very little infrared excess due to dust, and are notoriously difficult to separate from young Main-Sequence stars. We also discuss here the so-called “transition disk” objects which are YSOs without an inner disk but containing an optically thick outer disk (see in this context, e.g., Greene et al., 1994; Lada, 1987; Gutermuth et al., 2009; Kang et al., 2017).

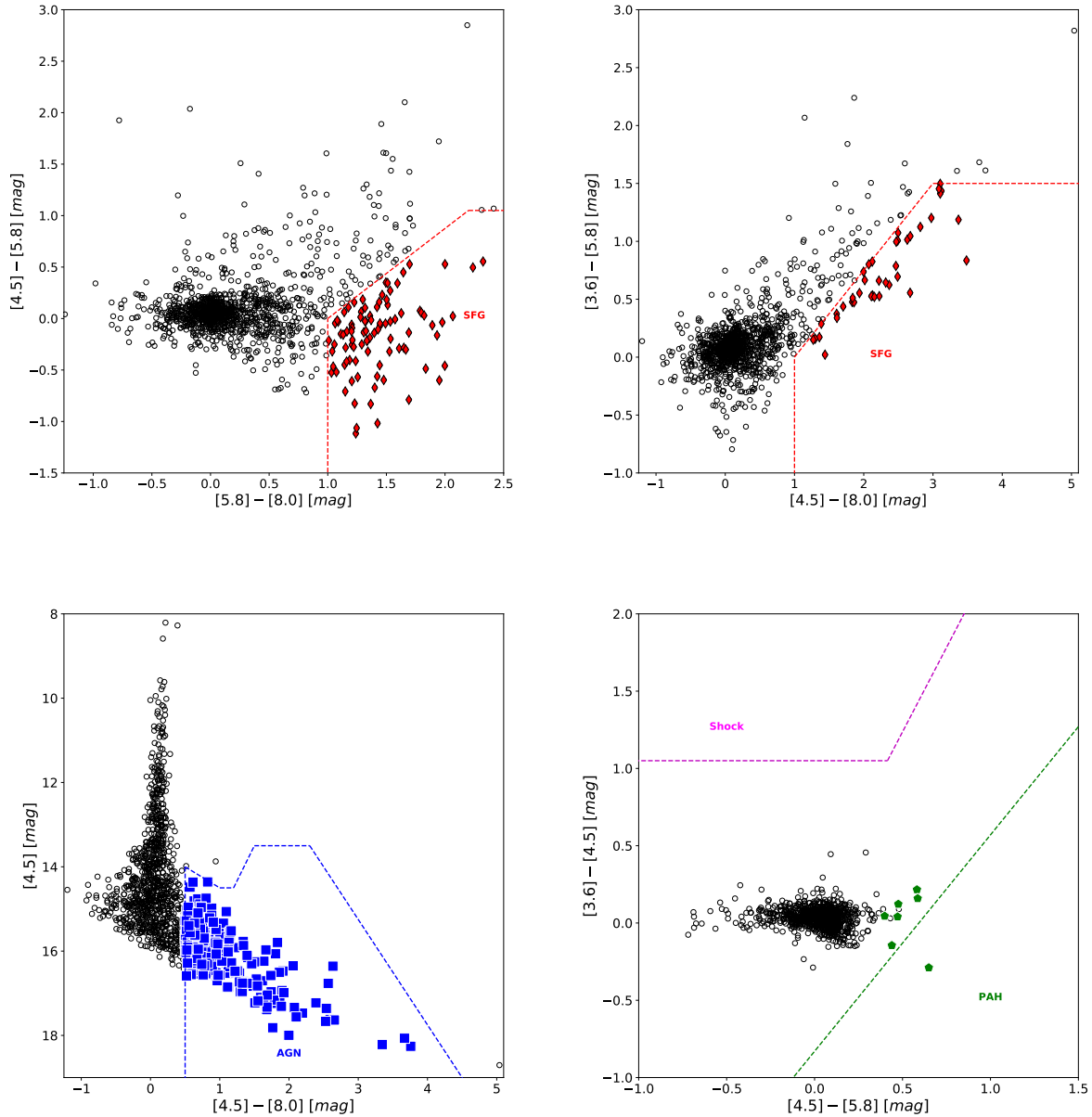


Figure 4.4: IRAC color-color diagrams for 1,319 sources from the SEIP query for the central region of DC 314.8–5.1. Displayed are the selection cuts applied following [Gutermuth et al. \(2009\)](#), in order to remove SFGs (marked with red diamonds; top panels), AGN (blue squares; bottom-left), as well as Galactic-scale unresolved shocks and unresolved PAH emission sources (green pentagons; bottom-right). The cuts are summarized in equations 4.7–4.10 of Appendix 4.6.3.

4.3.1 IRAC & 2MASS Source Selection

For the selection of the YSO candidates based on the infrared colors, we perform a survey of the region with a radius of $5'$ around the central position of the cloud, RA(J2000) = 14h 48m 29.0s and Dec(J2000) = $-65^\circ 15' 54.0''$, with the Spitzer Enhanced Imaging Products (SEIP) source list. First, we restrict all sources to have a signal-to-noise $\text{SNR} > 5$ in all four IRAC bands, excluding in this way unresolved extended sources and sources with only upper limits in any band. This returns a total of 1,319 sources. From those, we attempt to separate out YSOs, following the color cuts discussed in [Gutermuth et al. \(2009\)](#), [Winston et al. \(2019\)](#), and [Karska et al. \(2022\)](#).

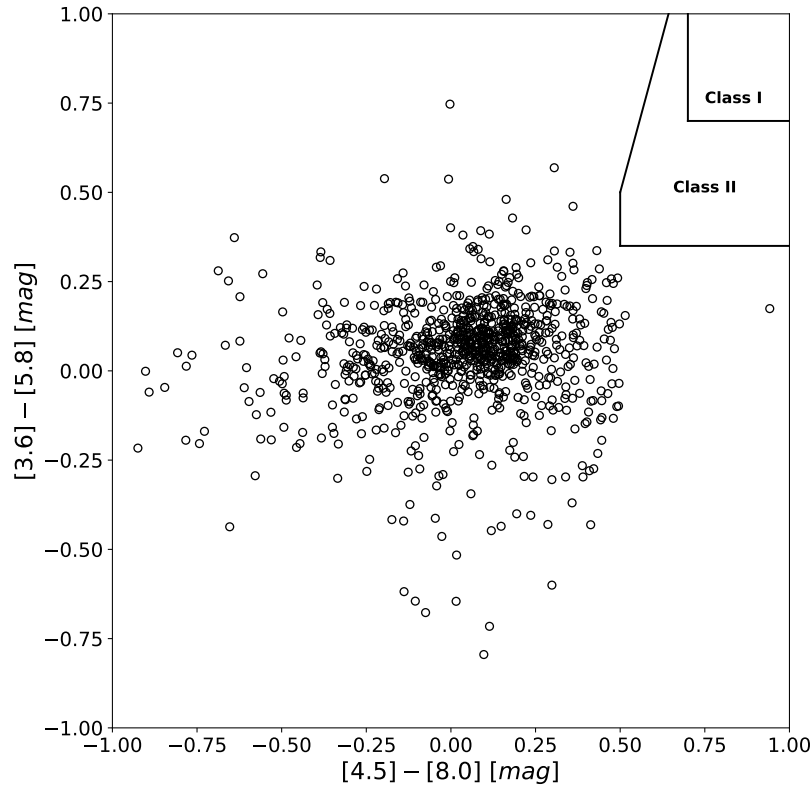


Figure 4.5: IRAC color-color diagram for 924 sources from the SEIP query for the central region of DC 314.8–5.1, remaining after removing extragalactic and Galactic contaminants (see Figure 4.4). Displayed are the selection cuts from [Gutermuth et al. \(2009\)](#), to identify Class I and Class II YSOs.

In particular, with the cuts of [Gutermuth et al. \(2009\)](#), summarized in equations 4.7–4.10 of Appendix 4.6.3, we remove extragalactic contaminating sources, including 132 star-forming galaxies (SFGs), and 256 active galactic nuclei (AGN). The corresponding SFG color cuts are shown in the top two panels of Figure 4.4, while the AGN color cuts are shown in the bottom-left

panel of the Figure. We also check for the presence of any Galactic-scale unresolved shocks or unresolved PAH emission sources, by applying color cuts given in equations 4.11–4.13 of Appendix 4.6.3, and displayed in the bottom-right panel of Figure 4.4. All these cuts provide a total of 924 potential YSOs within the central region of our cloud.

For those 924 sources, we then apply the Gutermuth et al. (2009) selection cuts for Class I and Class II YSOs, as summarized in equations 4.14–4.16 of Appendix 4.6.3, and visualized in Figure 4.5. These selections yield no YSO candidates of either Class I or II.

Following this lack of detection, we further investigate sources in the same region that are lacking robust ($\text{SNR} < 5$) detections in IRAC $5.8\ \mu\text{m}$ or IRAC $8.0\ \mu\text{m}$, but still with $\text{SNR} > 5$ detections in IRAC $3.6\ \mu\text{m}$ and IRAC $4.5\ \mu\text{m}$, and in addition with the caveat that they contain significant ($\sigma < 0.1\ \text{mag}$) detections in 2MASS bands H and K_s. We find 18 sources that match these criteria, each of which represents confident measurements in J, H, and K 2MASS bands. Following the cuts presented in Winston et al. (2019), and summarized in equations 4.17–4.20 of Appendix 4.6.4, we however find no sources within this sample that meet the criteria needed for a YSO detection.

4.3.2 WISE Source Selection

While the Spitzer selection for YSOs is indeed the most robust detection process, it does not consider the more evolved Class III objects. For robustness, we use the AllWISE catalog in order to identify any potential Class II YSOs within DC 314.8–5.1, as discussed in Koenig & Leisawitz (2014); Fischer et al. (2016); Kang et al. (2017), and Marshall et al. (2019). The search for sources included in the AllWISE catalog was performed for the same region as the IRAC source selection, i.e. within a radius of $5'$, returns 618 sources in total. For our selection, we follow the cuts presented in (Kang et al., 2017), first to remove any sources that are likely extragalactic contaminating objects (SFGs and AGN), along with the Galactic-scale unresolved shock and PAH emission regions (see equations 4.22–4.25 in Appendix 4.6.6), and next to select Class I YSOs, Class II YSOs, and Transition Disks (equations 4.26–4.28 in Appendix 4.6.6). The cuts are visualized in Figure 4.6.

These selections leave us with one source within the Class II region, and 34 sources occupying the potential Class III region of the color diagrams. We note here, however, that Kang et al. (2017) clarifies that the objects contained in Class III cannot be confidently distinguished from unrelated field stars in the mid-infrared. It is with this in mind that we inspect these sources utilizing the Gaia survey (see the next section), in order to rule out any non-associated sources.

The identified WISE source J144752.17-651601.1 (RA = 221.9674127, Dec = –65.266982) fulfilling the color criteria for a Class II YSO, was previously identified as a possible YSO candidate by Whittet (2007) based on the 2MASS survey performed therein.

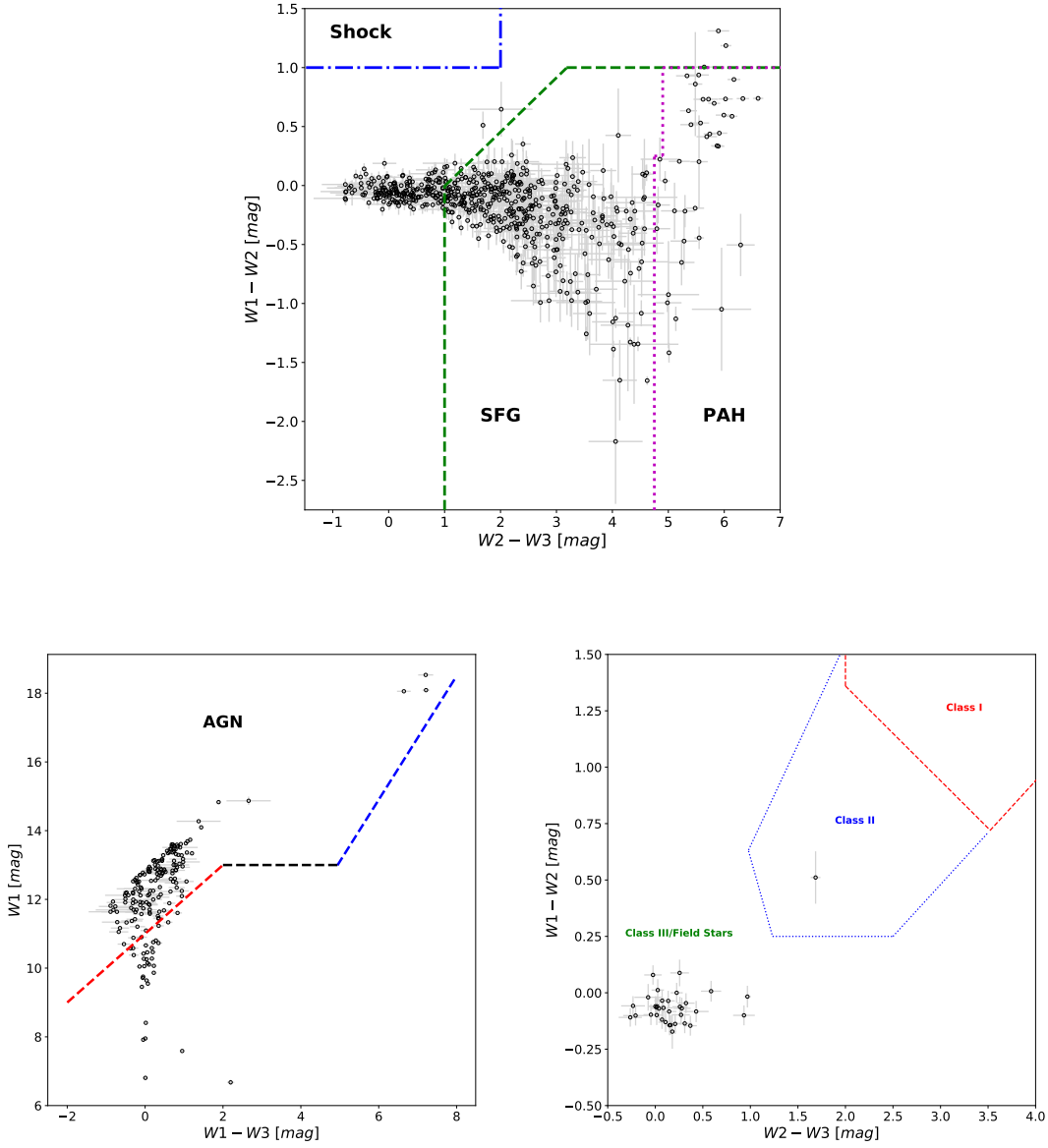


Figure 4.6: Top: $W1-W2$ vs. $W2-W3$ color-color diagram for all 618 sources from the AllWISE query for the central region of DC 314.8–5.1. The regions enclosed by the regions being: blue dot dashed - shock emission knots, green dashed - SFGs, and magenta dotted - PAH emission. **Bottom left:** $W1$ vs $W1-W3$ diagram for the AllWISE after removing SFGs and unresolved shock or PAH emission regions. Red dashed line marks the selection criteria for any contaminating AGN in our sample, all sources below this red line are potential YSOs. **Bottom right:** $W1-W2$ vs. $W2-W3$ color-color diagram for the remaining 35 YSO candidates among the AllWISE sources. The regions enclosed by the red dashed region are Class I YSOs, by the blue dotted region are Class II objects, and sources outside of this region being either Class III or reddened Field Stars. All selection cuts are from (Kang et al., 2017).

4.3.3 Gaia Parallax Measurements

Following the WISE selection criteria, we inspect the 35 sources identified as plausible YSO candidates, utilizing parallax measurements with the superb Gaia’s spatial resolution of $0.4''$.

First, we identify the C1 candidate as not being associated with DC 314.8–5.1 due to its measured parallax. C1 is located at RA = 14h 47m 52.2s and Dec = $-65^\circ 16' 1.0''$, with a Gaia measured parallax of 0.073 ± 0.096 . Inspecting the [Bailer-Jones et al. \(2021\)](#) catalog, they provide the distance to this star as $6.67^{+3.75}_{-2.25}$ kpc. Even at the highest error measurement, this would equate to a distance of 4.42 kpc, positioning this star far beyond the extents of our cloud. The remaining 34 potential YSO candidates have each coincided with a Gaia source and all but one have been ruled out based on their parallax measurements which exceed the acceptable distance range. The one remaining Class III YSO candidate, with acceptable parallax, is J144834.41–651145.4, located at RA = 14h 48m 34.4s and Dec = $-65^\circ 11' 54.5''$, denoted hereafter as C2. While there is a Gaia source with a stated parallax range coincident with C2, 1.27 ± 1.57 , within the WISE resolution of $6''$ of this source, there are two additional Gaia associations with parallax and simple computed distances far past DC 314.8–5.1. We inspect these entries in [Bailer-Jones et al. \(2021\)](#), finding that their distances are all constrained to be > 1 kpc. Due to the superior distance measurement methods presented in [Bailer-Jones et al.](#), we rule this source as being a background star heavily reddened by dust along the line of sight. This is not surprising as we do not expect any YSO detections within our cloud, and many WISE identified Class III objects are consistent with reddened field stars.

4.3.4 Pre-Main Sequence Stars in Swift XRT Data

PMSs are the established X-ray emitters, with the corresponding X-ray luminosities 10–10,000 times above the levels of X-ray luminosities characterizing the old Galactic disk population (see, e.g., [Preibisch & Feigelson, 2005](#); [Tsuboi et al., 2014](#)). They are routinely detected with instruments such as Chandra X-ray Observatory in various types of molecular clouds, due to the fact that their keV photons are able to penetrate the heavy extinction of dusty star-forming regions (e.g., [Wang et al., 2009](#); [Kuhn et al., 2010](#)). The bright members of the PMS population revealed by such studies are typically well modelled with the Astrophysical Plasma Emission Code (APEC; [Smith et al., 2001](#)), with temperatures of the order of a few/several keV, low abundances, and 0.5–10 keV luminosities of the order of 10^{30} erg s $^{-1}$.

In order to compare the expected level of potential PMS in our cloud with that of the S source detected in our Swift XRT short pointing, first we calculate the Galactic hydrogen column density in the direction of the target, utilizing the NHtot tool provided through HESEARC as well as the Chandra tool Colden. Given that our source is only at 432 pc distance, the resulting values $N_{\text{H,Gal}} \simeq 3.2 \times 10^{21}$ cm $^{-2}$ and $\simeq 3.6 \times 10^{21}$ cm $^{-2}$, respectively, are clearly an overestimation for the real column density along the line of sight. Nonetheless, in all our flux estimates below we conservatively adopt the value $N_{\text{H,Gal}} \simeq 3 \times 10^{21}$ cm $^{-2}$.

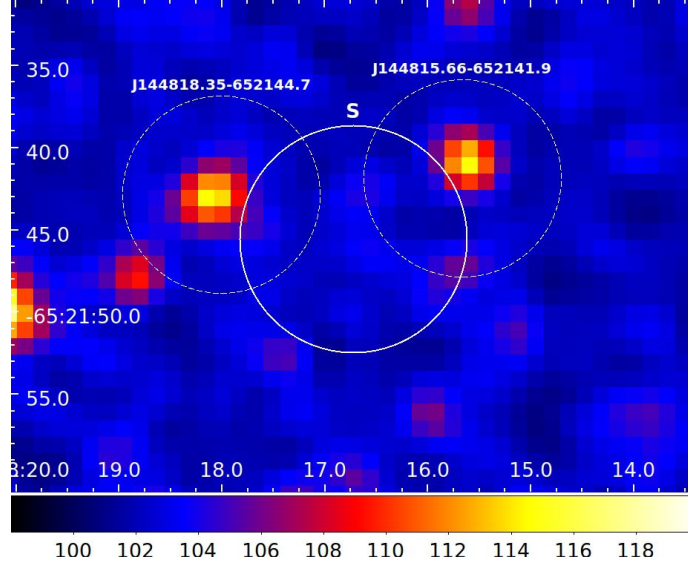


Figure 4.7: Image of the 2MASS combined color image of the Swift detected source. Colorbar indicates the intensity scale from 98–120 cts. S marks the position of the Swift detected source with a $6.9''$ radius circle consistent with the position error of the detection. Two white dashed circles represent the potential WISE counterparts, each with a $6''$ radius.

In addition to the Galactic diffuse ISM fraction, one must take into account also the intrinsic absorption within the cloud itself. For this, assuming a cloud’s mean gas density of 10^4 cm^{-3} and a spatial scale of 0.3 pc, we estimate roughly the corresponding column density at the level of $N_{\text{H, int}} \simeq 10^{22} \text{ cm}^{-2}$. Again, this should be considered as an upper limit for the intrinsic absorption value. Assuming therefore the APEC spectral model with temperature $kT = 2 \text{ keV}$, metallicity $Z = 0.2 Z_{\odot}$, and the absorbing column densities as estimated above, the $0.3–10 \text{ keV}$ XRT count rate $4.1^{+1.8}_{-1.4} \times 10^{-3} \text{ cts s}^{-1}$, corresponds to the unabsorbed flux of $F_{0.3–10 \text{ keV}} \simeq 4^{+1.7}_{-1.4} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, i.e. the isotropic intrinsic luminosity of $L_{0.3–10 \text{ keV}} \simeq 0.9^{+0.4}_{-0.3} \times 10^{31} \text{ erg s}^{-1}$ if at the distance of DC 314.8–5.1. This would be rather high for a PMS, although one should note that, by decreasing the intrinsic column density down to $N_{\text{H, int}} \simeq 10^{21} \text{ cm}^{-2}$ — as could be more appropriate keeping in mind that the source S is located at the far outskirts of the DC 314.8–5.1, rather than around the core of the cloud — the implied intrinsic luminosity decreases a bit down to $L_{0.3–10 \text{ keV}} \simeq 4.9^{+2.1}_{-1.7} \times 10^{30} \text{ erg s}^{-1}$.

The search for possible IR counterparts of the Swift XRT source S, returns two WISE/2MASS sources with the $0'.13–0'.14$ separation from the source S position, but with no redshift estimates. These are shown in Figure 4.7, and summarized in Table 4.1. The WISE colors for J144815.66-652141.9 ($W1-W2 = -0.62$ and $W2-W3 \geq 4.18$) indicate that the object could be a background luminous infrared galaxy (LIRG), or a starburst galaxy; the WISE colors of J144818.35-652144.7 ($W1-W2 = -0.31$ and $W2-W3 \geq 2.37$), on the other hand, are consistent with a regular star-forming galaxy (see Wright et al., 2010). One of these two sources is a likely counterpart of the Swift XRT source S, which as such does not represent a viable PMS candidate.

4.4 Discussions

YSOs, if present and related to the cloud, would appear as optical/infrared point sources for which the parallax distances, measured with Gaia, should agree with the distance to the cloud. YSOs can be separated from background stars due to the presence of infrared excess, primarily in the $1 - 30 \mu\text{m}$ range (Evans et al., 2009). In this context, we investigated the selection cuts from Kang et al. (2017), Winston et al. (2019), and Gutermuth et al. (2009), for point sources located within the spatial extent of DC 314.8–5.1. We followed these selections with a cross-identification with Gaia.

The infrared color-color cuts identified one Class II candidate, J144752.17-651601.1, also previously selected by Whittet (2007). This candidate, marked C1, is located in the western part of DC 314.8–5.1 and shows no UV or X-ray emission, see Figure 4.2 (lower right panel) and Figure 4.3 respectively. This YSO candidate was inspected and we found to have a Gaia association with a newly measured parallax of 0.073 ± 0.096 , which places the star at even the highest error range, far removed from the location of DC 314.8–5.1. In addition, the infrared selection identified 34 potential Class III sources, however, all of these sources have Gaia associations with parallax (Bailer-Jones et al., 2021) far away from the cloud.

All in all, the lack of any robust YSO detections confirms the pre-star forming state of the cloud, DC 314.8–5.1, initially discussed in Whittet (2007) and Kosmaczewski et al. (2022b). However, younger YSOs and protostars that are still heavily embedded within their cores may not be detectable by their infrared excesses due to the reprocessing of their infrared emission to longer wavelengths (Evans et al., 2009; Karska et al., 2018). In addition to those sources affected by reprocessing of emission, Class III sources can also be distinguished from background stars through their X-ray emission (Grosso et al., 2000). In the given XRT data we analyzed there are no detected PMS candidates. Our relatively short Swift-XRT exposure could probe the presence of point sources within the cloud only down to an unabsorbed 0.5–10 keV luminosity level of $\lesssim 10^{31} \text{ erg s}^{-1}$. Only the brightest PMSs can have luminosities of this order (Kuhn et al., 2010), and so much deeper X-ray imaging would be needed to investigate the bulk of the potential PMS population in DC 314.8–5.1. The spectral energy distribution (SED) of the DC 314.8–5.1 system, within the spectral range

Table 4.1. Infrared Source Associations with X-ray Source

WISE Source	2MASS Source	RA [deg]	DEC [deg]	Separation arcsec	W1–3.4 μm [mag]	W2–4.6 μm [mag]	W3–12 μm [mag]	W4–22 μm [mag]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
J144815.66–652141.9	J14481560–6521409	222.06526	-65.36164	0.126	15.048 ± 0.040	15.665 ± 0.135	12.705	8.891
J144818.35–652144.7	J14481808–6521430	222.07499	-65.36192	0.141	14.672 ± 0.040	14.984 ± 0.082	12.614	8.920

Note. — **col(1)** — name of the WISE source; **col(2)** — name of the respective 2MASS counterpart; **col(3)** — Right Ascension; **col(4)** — Declination; **col(5)** — angular separation between the central position of the infrared source and the central positioning of the Swift XRT source S; **col(6)–(9)** — fluxes in the respective WISE bands (W1–W4) in magnitudes.

from microwaves up to UV is composed of the three main components (Figure 4.8). One is the thermal emission of the dominant cold gas and dust, the other is the emission of a warm and hot dust photoionized and heated by the field star, HD 130079, and finally the third spectral component is the HD 130079 photospheric emission itself. Here, we do not discuss the lower-frequency microwave and radio emission of the system (frequencies below 100 GHz), nor do we analyze the high-energy diffuse emission of the cloud (at X-ray and γ -ray frequencies), which will be both addressed in our follow-up work.

For the microwave segment of the SED, dominated by the cold gas and dust, we take the aperture fluxes from the Second Planck Catalogue of Compact Sources (PCCS2E; [Planck Collaboration et al., 2016a](#)) at 143, 217, 353, 545, and 857 GHz. In the infrared range, dominated by the radiative output of the warm and hot dust, we use the fluxes from the IRAS Point Source Catalog v.2.1 at 12, 25, 60, and 100 μm (see Section 4.2.1), the dedicated Spitzer IRS STARE observations of HD 130079 (obtained as a part of the Spitzer Proposal ID 50039, see Section 4.2.2), and the WISE fluxes at 3.4, 4.6, 12, and 22 μm (see Section 4.2.2). The near-infrared (filters *JHKL*) and optical (*UBV*) fluxes, representing the HD 130079 starlight, follow directly from the compilation by [Whittet \(2007](#), see Table 1 therein), with the addition of the *G* band flux from the EDR3 ([Gaia Collaboration et al., 2021](#)), and the UV 2250Å flux measured from our newly obtained Swift UVOT observations (see Section 4.2.2).

We have modelled the cold thermal component with a modified blackbody $B_\nu(T) \times (\nu/\nu_0)^\beta$, where

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \left[\exp\left(\frac{h\nu}{kT}\right) - 1 \right]^{-1}, \quad (4.1)$$

with the temperature $T = 14$ K that agrees with that of the PGCC model fit, but slightly smaller value for the spectral index $\beta = 1.5$ (see dark red solid curve in Figure 4.8; cf. Section 4.2.1). The far/mid-infrared (roughly 70 – 7 μm) emission of the system, is a complex superposition of the continua from multi-temperature dust, molecular lines, and PAH features, all generally decreasing in intensity away from the photoionizing star DC 314.8–5.1 (see [Kosmaczewski et al., 2022b](#)). The differences between the IRAS, WISE, and Spitzer flux measurements in this spectral range (at the corresponding frequencies), reflects therefore directly the different apertures of the instruments pointing at the star. In particular, the 12 μm Spitzer IRS flux measured from a region $4.7'' \times 11.3''$ around HD 130079, as given in Figure 4.8, is about a half of that measured with WISE, and a third of that measured with IRAS. For a very crude representation of this entire spectral component, here we adopt for illustration the simplest model consisting of the two modified blackbody components, with the temperatures of 50 K and 200 K, spectral indices $\beta = 2.0$, and normalization adjusted to match (the highest) IRAS fluxes (see the dark red dashed and dotted curves in Figure 4.8, respectively).

Finally, the photospheric emission of HD 130079, is modelled here assuming a simple blackbody spectrum with the temperature $T_\star = 10,500$ K, such that the bolometric stellar luminosity is

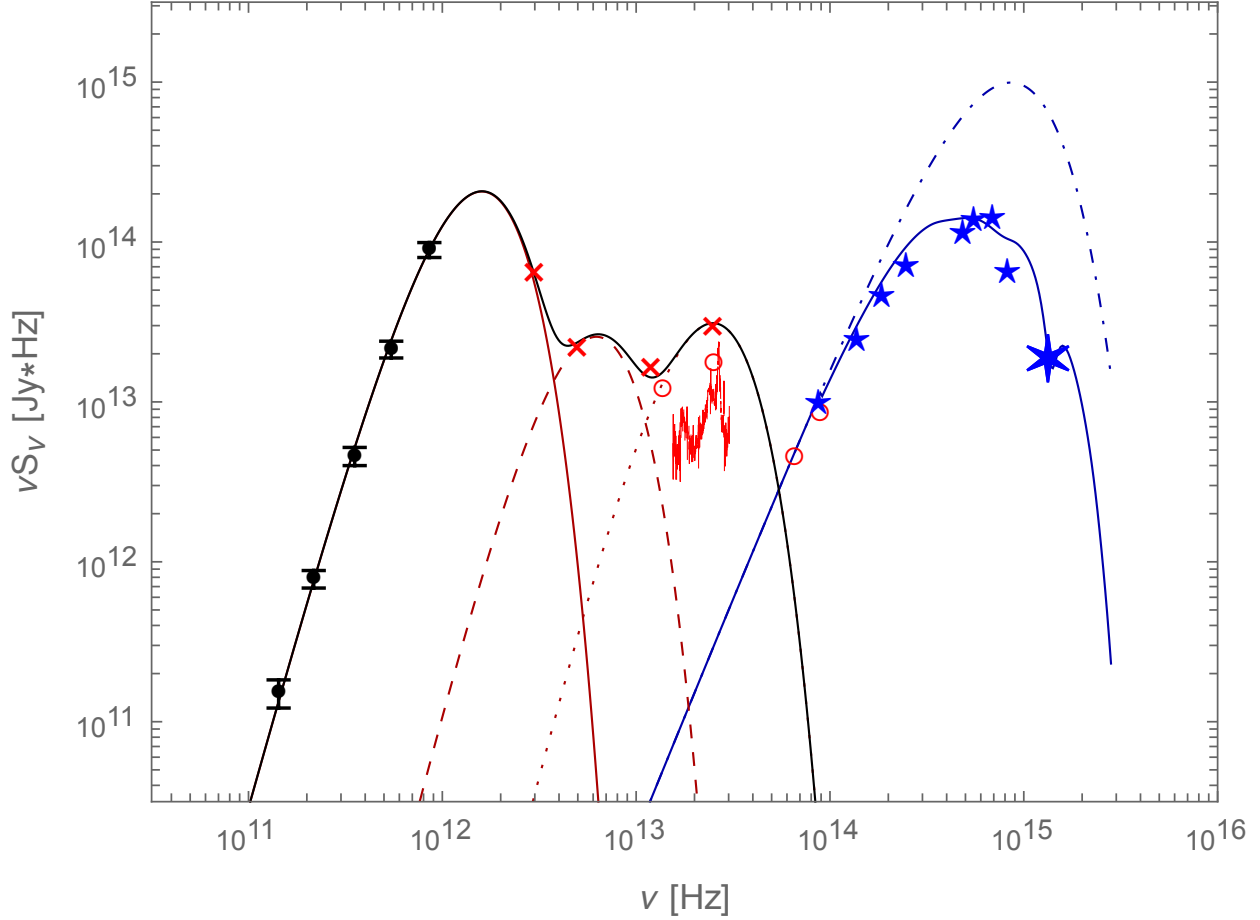


Figure 4.8: SED of the DC314.8-5.1 system, based on the observations with Planck (filled black circles), IRAS (red crosses), WISE (open red circles), Spitzer IRS STARE (thin red curve), ground-based telescopes and Gaia survey (small blue stars), and finally with the Swift UVOT (big blue star). Dark red solid, dashed, and dotted curves represent modified blackbody models for the emission of cold (14 K), warm (50 K), and hot (200 K) dust within the cloud, respectively; black solid curve denotes the total dust model. Dark blue dot-dashed curve corresponds to the intrinsic emission of the field star HD 130079, modelled as a blackbody with the temperature 10,500 K and the total luminosity of $3 \times 10^{35} \text{ erg s}^{-1}$; dark blue solid curve illustrates this intrinsic emission subjected to the interstellar reddening. See § 4.4 for description.

$L_\star = 4\pi R_\star^2 \sigma_{\text{SB}} T_\star^4 \simeq 3 \times 10^{35} \text{ erg s}^{-1}$, for the stellar radius $R_\star = 2.7 \times R_\odot$. This intrinsic emission,

$$F_\nu^{\text{int}} = \frac{B_\nu(T_\star)}{\int d\nu' B_{\nu'}(T_\star)} \left(\frac{R_\star}{D} \right)^2 \sigma_{\text{SB}} T_\star^4, \quad (4.2)$$

where $D = 432 \text{ pc}$ (denoted in Figure 4.8 by the dark blue dot-dashed curve), is next subjected to the interstellar reddening,

$$F_\nu = F_\nu^{\text{int}} \times e^{-0.4 A_\lambda \ln 10}, \quad (4.3)$$

using the Cardelli et al. (1989) empirical extinction law

$$\frac{A_\lambda}{E_{B-V}} = a(\lambda) R_V + b(\lambda), \quad (4.4)$$

with the coefficients $a(\lambda)$ and $b(\lambda)$ as given in equations 2–5 of Cardelli et al., and the values $E_{B-V} = 0.395$ and $R_V = 4.5$ (in excess over the averaged ISM value of $R_V = 3.1$) adopted from Whittet (2007). The reddened starlight (given by the solid dark blue curve in Figure 4.8), matches the gathered near-infrared-to-UV fluxes of the star reasonably well, including the 3.4 and 4.6 μm WISE fluxes, and the Swift UVOT 2250Å flux, even though no stellar photosphere reddening was included in our simple model.

The mass of the Planck source PGCC G314.77–5.14, has been estimated in Planck Collaboration et al. (2016c) as

$$M = \frac{D^2 F_\nu}{\kappa_\nu B_\nu(T)} \sim 10 M_\odot, \quad (4.5)$$

based on the measured 857 GHz flux density F_ν integrated over the solid angle $\Omega = \pi\theta^2/4$ (where θ is the geometric mean of the major and minor FWHM), which is effectively half the provided PGCC flux, with the adopted dust opacity $\kappa_\nu = 0.1 (\nu/1 \text{ THz})^\beta \text{ cm}^2 \text{ g}^{-1}$. The dust opacity function is however not exactly known, and depends strongly on the dust composition (see, e.g., D’Alessio et al., 2001). As a result, it is likely that with a more detailed prescription for the dust opacity, there is no real discrepancy between the Planck mass estimate for DC 314.8–5.1, and that following from the visual extinction analysis, in particular Whittet (2007) estimate for the mass of the *core* of the globule, $\gtrsim 50 M_\odot$, updated for the 432 pc distance.

The mass of the studied system — as an the isolated source at high Galactic latitudes — can be estimated not only from the continuum emission at radio-to-far-infrared frequencies, but also from the excess absorption seen in X-rays toward the cloud (see in this context Sofue & Kataoka, 2016), as well as from the high-energy γ -ray data provided by the Fermi-LAT (see Mizuno et al., 2022, and references therein). In the former case, a much deeper X-ray observations would be needed to estimate the absorbing hydrogen column density in various segments of the cloud. Concerning the latter, we only note at this point that, in the Fermi High-Latitude Extended Sources Catalog (FHES) by Ackermann et al. (2018), the integrated 1 GeV–1 TeV fluxes of the sources for which the spatial extension could be determined with high confidence in the LAT data, extend down to a few/several $\times 10^{-10} \text{ erg s}^{-1}$, while of those which appear point-like, about one magnitude lower, with a median

of $2.5 \times 10^{-10} \text{ erg s}^{-1}$. Meanwhile, the most basic estimate for the flux expected from DC 314.8–5.1 due to the interactions with high-energy CRs (assuming no CR overdensity with respect to the CR background), is

$$\begin{aligned} F(> E_\gamma) &\simeq 2 \times 10^{-13} \frac{M/10^5 M_\odot}{(D/\text{kpc})^2} \left(\frac{E_\gamma}{1 \text{ TeV}} \right)^{-1.7} \\ &\sim 2 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \end{aligned} \quad (4.6)$$

(see Gabici, 2013). In the above, we put $M = 160 M_\odot$ corresponding to the *total* mass of the cloud, the updated distance $D = 432 \text{ pc}$, and $E_\gamma = 1 \text{ GeV}$. This level of emission is promising for the dedicated Fermi-LAT studies, enabling, hopefully, a robust estimate of the mass in this pre-starforming system.

4.5 Conclusions

In this paper we have discussed the multi-wavelength properties of the dark globule, DC 314.8–5.1, through the dedicated observations with the Spitzer Space Telescope and the Swift-XRT and UVOT instruments, supplemented by the archival Planck, IRAS, WISE, 2MASS, and Gaia data. This investigation of the characteristics of the system, over a wide range of the electromagnetic spectrum, has led to the following conclusions:

1. We have confirmed that DC 314.8–5.1 is a pre-stellar core, with no YSO candidates present within the extent of the system.
2. With the Swift-XRT observations, we could probe the PMS population down to a luminosity level of $\lesssim 10^{31} \text{ erg s}^{-1}$. This level excludes the brightest PMSs, and so deeper observations are needed to explore the presence of less luminous objects.
3. We investigated the SED of the DC 314.8–5.1 system including the incident star HD 130079, confirming the presence of a hot dust (with temperatures up to 200 K), in addition to the dominant 14 K gas component.
4. We comment on the variation in estimates for the mass of the cloud, ranging from $\simeq 10 M_\odot$ based on the Planck photometry for the core of the globule, up to $\gtrsim 50 M_\odot$ following from the visual extinction characteristics, pointing out in particular that the discrepancy may be due to the poorly constrained dust opacity for this particular system, affecting the photometric estimate. We also note in this context, that the cloud should be detected in high-energy γ -rays with Fermi-LAT, given that the estimate for the total mass of the globule $\sim 160 M_\odot$ is correct.

All in all, DC 314.8–5.1 is the ideal pre-stellar core candidate for deeper observations, especially in high-energy X-ray and γ -ray ranges, given its location below the Galactic plane (-5 deg), and its proximity (432 pc).

4.6 Appendix

4.6.1 A: Mid-Infrared Images of DC 314.8–5.1

In Figure 4.9 we present the Spitzer IRAC images of the DC 314.8–5.1 region at 3.6, 4.5, 5.8, and 8.0 μm . In Figure 4.10 we show the corresponding WISE images at 3.4 (W1), 4.6 (W2), 12 (W3), and 22 μm (W4).

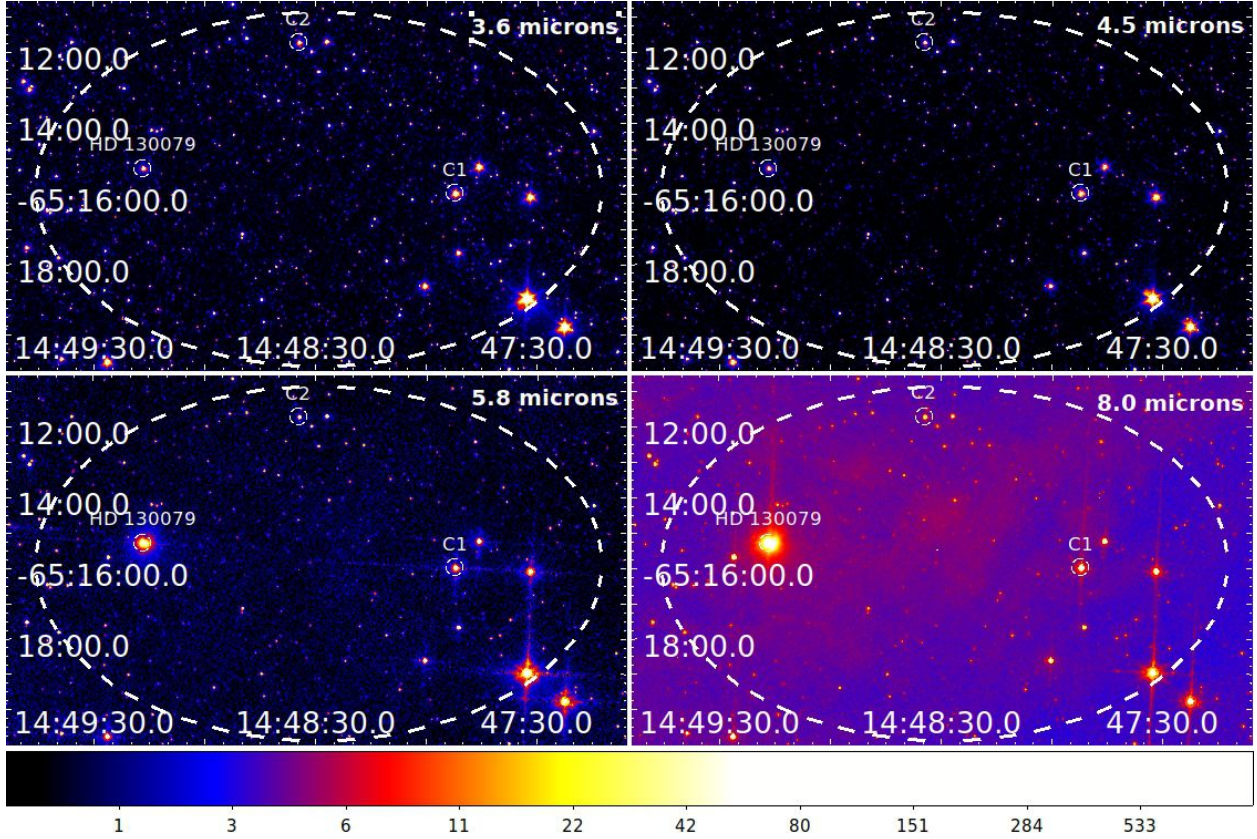


Figure 4.9: Spitzer IRAC band maps of the DC 314.8–5.1 region. **Top** (left) Channel 1 at 3.6 μm , (right) channel 2 at 4.5 μm , **Bottom** (left) channel 3 at 5.8 μm , and (right) channel 4 at 8.0 μm . White dashed ellipse marks the primary extent of DC 314.8–5.1. Color bar is set with a minimum of 0 and a maximum value of 2000 MJy/sr on a log scale. HD 130079 field star is marked in the left of the image, C1 marks the YSO candidate identified by Whittet (2007), and C2 marks the YSO candidate identified in this work.

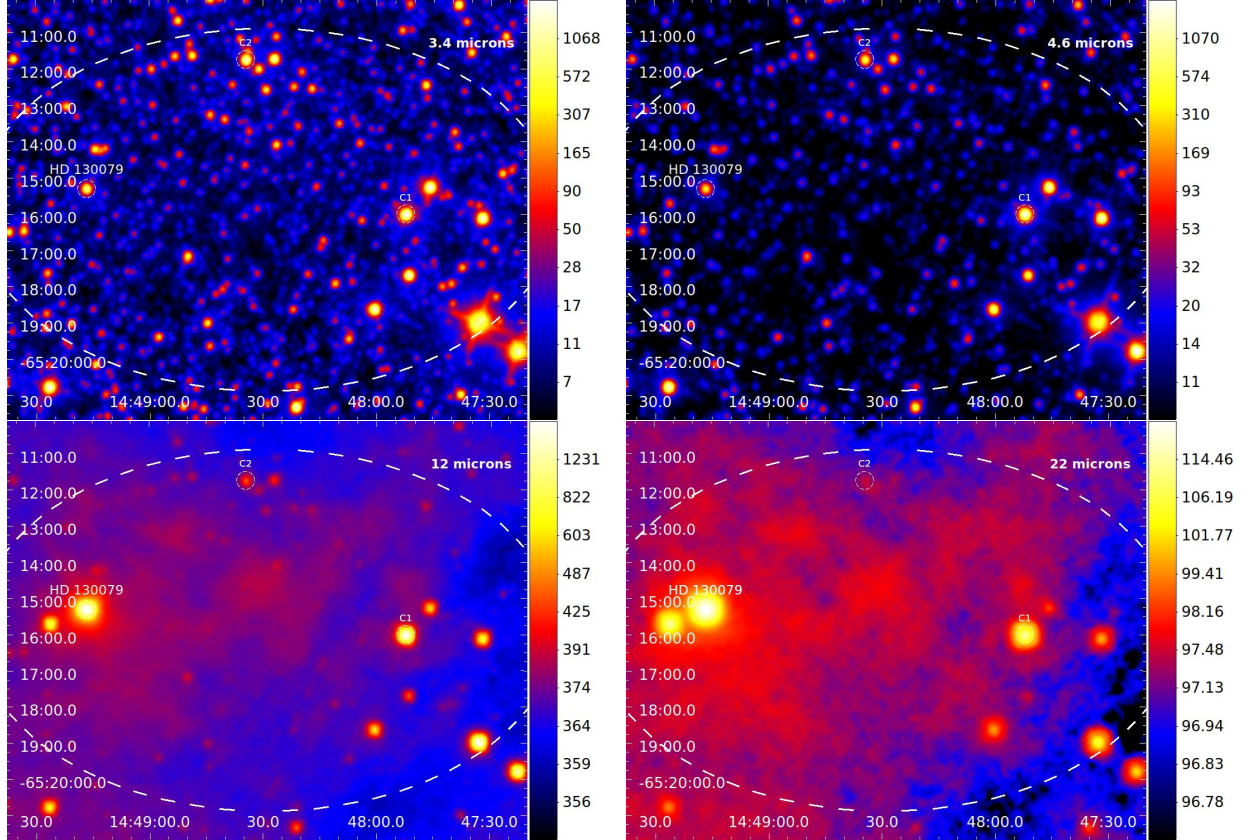


Figure 4.10: Log scaled WISE maps of the DC 314.8–5.1 region. **Top** (left) Channel W1 at $3.4\ \mu\text{m}$, with a scale of 5.5–2000 in units of Digital Number (DN), (right) channel W2 at $4.6\ \mu\text{m}$, with a scale of 9–2000 DN **Bottom** (left) channel W3 at $12\ \mu\text{m}$, with a scale of 355–2000 DN, and (right) channel W4 at $22\ \mu\text{m}$, with a scale of 96.75–130 DN. White dashed ellipse marks the primary extent of DC 314.8–5.1. Color bar is set on a log scale. HD 130079 field star is marked in the left of the image, C1 marks the YSO candidate identified by [Whittet \(2007\)](#), and C2 marks the YSO candidate identified in this work.

4.6.2 B: ROSAT and Swift XRT Comparison

In Figure 4.11, we compare the ROSAT full-band 0.1 – 2.4 keV image of the DC 314.8–5.1 region, with the corresponding images from the Swift XRT soft band 0.3 – 2.0 keV as well as hard band 2 – 10 keV, including for a reference also the MIPS 24 μm image of the system. We note that, assuming the emission model specified in Section 4.3.4, the PSPC 0.1 – 2.4 keV count rate for ROSAT J144833.7–651738 of $0.0175 \pm 0.0082 \text{ cts s}^{-1}$, would correspond to the Swift XRT PC 0.3 – 10 keV count rate of $(19.7 \pm 9.2) \times 10^{-3} \text{ cts s}^{-1}$ for $N_{\text{H,int}} \simeq 10^{22} \text{ cm}^{-2}$, and $(13.1 \pm 6.2) \times 10^{-3} \text{ cts s}^{-1}$ for $N_{\text{H,int}} \simeq 10^{21} \text{ cm}^{-2}$, while the estimated XRT 0.3 – 2.0 keV count rate for the source S is $4.1^{+1.8}_{-1.4} \times 10^{-3} \text{ cts s}^{-1}$, and the 3σ upper limit at the nominal position of the center of the cloud/ROSAT source, calculated with the The Living Swift XRT Point Source Catalogue online tool³, is $\simeq 3 \times 10^{-3} \text{ cts s}^{-1}$.

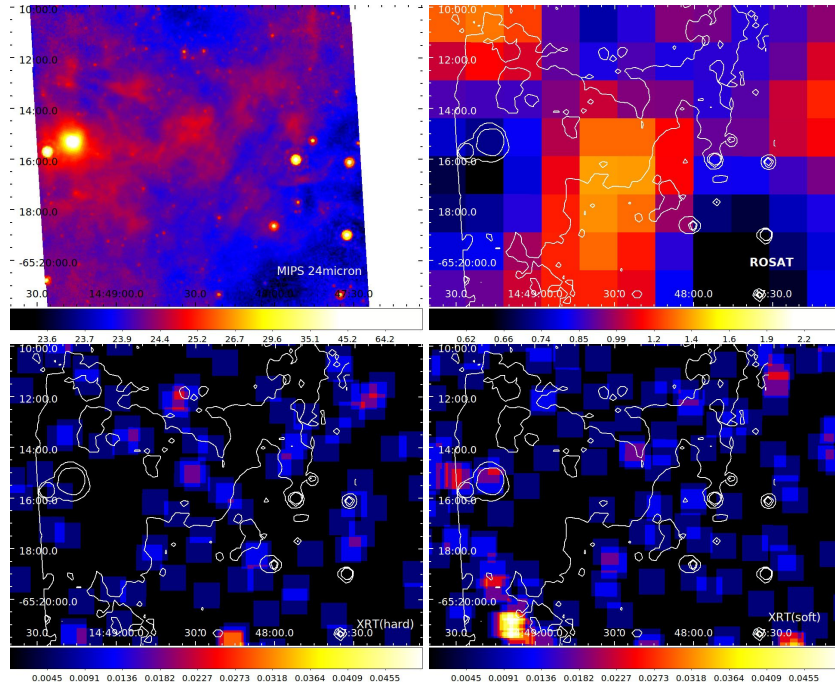


Figure 4.11: **Top** (left) Spitzer MIPS 24 μm image of the DC 314.8–5.1 region. Color bar is set with a minimum of 23.5 to 100 MJy/sr on a log scale. White contours in the following panels are set based on the MIPS emission with log scale levels set at 24.1, 25.05, and 26 MJy/sr (right) ROSAT full-band 0.1 – 2.4 keV image of the same region, with Spitzer MIPS contours superimposed for a reference. Color bar is set with a range 0.6–2.5 cts on a sqrt scale with smoothing parameters as in Figure 4.1. **Bottom** Swift XRT hard-band 2 – 10 keV and soft-band 0.3 – 2.0 keV images of the same region (left and right, respectively), smoothed with boxcar of kernel radius 6, and with black parameter of 2×2 to match the ROSAT resolution, and with Spitzer MIPS contours superimposed for a reference. Color bar is set with a range of 0–0.05 photons on a log scale.

³<https://www.swift.ac.uk/LSXPS/>

4.6.3 C: IRAC color Cuts by Gutermuth et al. (2009)

For the sources with robust ($\text{SNR} > 5$) detections in all IRAC bands 3.6, 4.5, 5.8, and $8.0 \mu\text{m}$, the Gutermuth et al. (2009) color cuts for removing active SFGs, are

$$\begin{aligned} [4.5] - [5.8] &< 1.05 \times ([5.8] - [8.0] - 1.0)/1.2, \\ [4.5] - [5.8] &< 1.05, \\ [5.8] - [8.0] &> 1, \text{ and} \\ [4.5] &> 11.5, \end{aligned} \tag{4.7}$$

or

$$\begin{aligned} [3.6] - [5.8] &< 1.5 \times ([4.5] - [8.0] - 1)/2, \\ [3.6] - [5.8] &< 1.5, \\ [4.5] - [8.0] &> 1, \text{ and} \\ [4.5] &> 11.5. \end{aligned} \tag{4.8}$$

The color cuts for removing AGN are, on the other hand,

$$\begin{aligned} [4.5] - [8.0] &> 0.5, \\ [4.5] &> 13.5 + ([4.5] - [8.0] - 2.3)/0.4, \text{ and} \\ [4.5] &> 13.5; \end{aligned} \tag{4.9}$$

moreover, any source flagged as an AGN must also obey at least one of the following criteria:

$$\begin{aligned} [4.5] &> 14 + ([4.5] - [8.0] - 0.5), \text{ or} \\ [4.5] &> 14.5 - ([4.5] - [8.0] - 1.2)/0.3, \text{ or} \\ [4.5] &> 14.5. \end{aligned} \tag{4.10}$$

Additionally, Galactic-scale unresolved shock emission knots, can be removed with the color cuts

$$\begin{aligned} [3.6] - [4.5] &> 1.2 \times ([4.5] - [5.8] - 0.3)/0.55 + 0.8 \\ [4.5] - [5.8] &\leq 0.85, \text{ and} \\ [3.6] - [4.5] &> 1.05, \end{aligned} \tag{4.11}$$

while unresolved PAH emission sources, can be removed by applying

$$\begin{aligned} [3.6] - [4.5] - \sigma_{12} &\leq 1.4 \times (([4.5] - [5.8]) + \sigma_{23} - 0.7) + 0.15, \text{ and} \\ [3.6] - [4.5] - \sigma_{12} &< 1.65, \end{aligned} \tag{4.12}$$

where

$$\begin{aligned} \sigma_{12} &= \sigma[[3.6] - [4.5]], \text{ and} \\ \sigma_{23} &= \sigma[[4.5] - [5.8]], \end{aligned} \tag{4.13}$$

with σ as the error in each respective band and added in quadrature for individual colors. The selection criteria for Class I YSOs, are

$$\begin{aligned} [4.5] - [5.8] &> 0.7, \text{ and} \\ [3.6] - [4.5] &> 0.7. \end{aligned} \quad (4.14)$$

Class II YSOs, are the sources not selected with the above cuts, but instead following:

$$\begin{aligned} [4.5] - [8.0] - \sigma_{24} &> 0.5 \\ [3.6] - [5.8] - \sigma_{13} &> 0.35 \\ [3.6] - [5.8] + \sigma_{13} &\leq 0.140.04 \times (([4.5] - [8.0] - \sigma_{24}) - 0.5) + 0.5, \text{ and} \\ [3.6] - [4.5] - \sigma_{12} &> 0.15, \end{aligned} \quad (4.15)$$

where

$$\begin{aligned} \sigma_{24} &= \sigma [[4.5] - [8.0]], \text{ and} \\ \sigma_{13} &= \sigma [[3.6] - [5.8]]. \end{aligned} \quad (4.16)$$

4.6.4 D: IRAC–2MASS color Cuts by Winston et al. (2019)

For the sources with no ($\text{SNR} < 5$) detections in IRAC 5.8 μm or IRAC 8.0 μm detections, but with robust ($\text{SNR} > 5$) detections in IRAC 3.6 μm and IRAC 4.5 μm , as well as significant ($\sigma < 0.1$ mag) detections in 2MASS bands H and K_s , the [Winston et al. \(2019\)](#) color cuts for the YSO detection are

$$\begin{aligned} [3.6] - [4.5] - \sigma_{12} &> 0.101, \\ [K_s] - [3.6] - \sigma_{K1} &> 0.5, \text{ and} \\ [K_s] - [3.6] - \sigma_{K1} &> -2.857 \times ([3.6] - [4.5] - \sigma_{12} - 0.101) + 1.5, \end{aligned} \quad (4.17)$$

where, once again, σ is the error in each respective band, and is added in quadrature for colors as follows,

$$\sigma_{K1} = \sqrt{\sigma [K_s]^2 + \sigma [3.6]^2}. \quad (4.18)$$

For those sources which have robust IRAC 8.0 μm detections, The YSO selection criteria are

$$[K_s] - [8.0] - \sigma_{K4} > 3, \quad (4.19)$$

where

$$\sigma_{K4} = \sqrt{\sigma [K_s]^2 + \sigma [8.0]^2}. \quad (4.20)$$

Note that in this we do not use the [Gutermuth et al. \(2009\)](#) cuts, as we do not have distance measurements for all of the detected sources, and so cannot accurately determine the line of sight extinction.

4.6.5 E: IRAC–MIPS color Cuts by Gutermuth et al. (2009)

For the sources bright in the MIPS $24\mu\text{m}$ band ($[24] < 7\text{ mag}$), and with strong ($\text{SNR} > 5$) detections IRAC $3.6\mu\text{m}$ and IRAC $4.5\mu\text{m}$, the Gutermuth et al. (2009) “Phase 3” selection cuts for heavily embedded protostars, are

$$\begin{aligned} [24] &< 7, \\ [X] - [24] &> 4.5, \\ [3.6] - [5.8] &> 0.5, \\ [4.5] - [24] &> 4.5, \text{ and} \\ [8.0] - [24] &> 4. \end{aligned} \tag{4.21}$$

where $[X]$ denotes the longest IRAC band detected.

4.6.6 F: WISE color Cuts by Kang et al. (2017)

For the targets selected from the AllWISE catalog, the color cuts presented in Kang et al. (2017) to remove SFGs, are as follows:

$$\begin{aligned} W2 - W3 &> 1.0, \\ W1 - W2 &< 1.0, \\ W1 - W2 &< 0.46 \times (W2 - W3) - 0.466, \text{ and} \\ W1 &> 12.0 \text{ or } W2 > 11.0. \end{aligned} \tag{4.22}$$

Following these cuts, the criteria for identifying and removing AGN, are as follows:

$$\begin{aligned} W1 &> 1.8 \times (W1 - W3) + 4.1, \text{ and} \\ W1 &> 13.0 \text{ or } W2 > 12.0, \text{ or} \\ W1 &> W1 - W3 + 11.0. \end{aligned} \tag{4.23}$$

The cuts for removing Galactic-scale unresolved shocks, are

$$\begin{aligned} W1 - W2 &> 1.0, \text{ and} \\ W2 - W3 &< 2.0. \end{aligned} \tag{4.24}$$

Finally, the cuts for removing unresolved PAH emission sources, are

$$\begin{aligned} W1 - W2 &< 1.0, \text{ and} \\ W2 - W3 &> 4.9, \text{ or} \\ W1 - W2 &< 0.25, \text{ and} \\ W2 - W3 &> 4.75. \end{aligned} \tag{4.25}$$

CHAPTER 4. MULTIWAVELENGTH SURVEY OF DC 314.8–5.1

The selection criteria for Class I YSOs, are

$$\begin{aligned} W1 - W2 &> -0.42 \times (W2 - W3) + 2.2 , \\ W1 - W2 &> 0.46 \times (W2 - W3) - 0.9 , \\ W2 - W3 &> 2.0 , \text{ and} \\ W2 - W3 &< 4.5 . \end{aligned} \tag{4.26}$$

Class II YSOs are selected according to

$$\begin{aligned} W1 - W2 &> 0.25 , \\ W1 - W2 &< 0.9 \times (W2 - W3) - 0.25 , \\ W1 - W2 &> -1.5 \times (W2 - W3) + 2.1 , \\ W1 - W2 &> 0.46 \times (W2 - W3) - 0.9 , \text{ and} \\ W2 - W3 &< 4.5 . \end{aligned} \tag{4.27}$$

Transition Disks are classified as

$$\begin{aligned} W3 - W4 &> 1.5 , \\ W1 - W2 &> 0.15 , \\ W1 - W2 &< 0.8 , \\ W1 - W2 &> 0.46 \times (W2 - W3) - 0.9 , \text{ and} \\ W1 &\leq 13.0 . \end{aligned} \tag{4.28}$$

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Chapter 5

Summary and Future Prospects

This thesis has laid out the three research projects that were performed to deepen our understanding of cosmic dust on various astrophysical scales across a broad range of wavelengths. This was done through the study of a sample of young radio galaxies and through the dedicated study of the exemplary object DC 314.8–5.1.

We began our study with an inspection of a sample of the youngest radio galaxies. In our inspection, our main findings were: (i) sources in which the MIR emission is dominated by the ISM component uniformly populate the region occupied by galaxies with a wide range of pronounced star formation activity ($\geq 0.5 M_{\odot} \text{ yr}^{-1}$), (ii) the triggering of radio jets in AGN does not differentiate between elliptical hosts with substantially different fractions of young stars; instead there is a relationship between the jet duty cycle and the ongoing star formation, and (iii) the distribution of the sub-sample of our sources with $z < 0.4$ on the low-resolution MIR vs. absorption-corrected X-ray luminosity plane is consistent with the distribution of a sample of local AGN.

The second aspect of my inspection of cosmic dust was the thorough spectroscopic inspection of the dark cloud, DC 314.8–5.1, suspected to be just prior to the onset of star formation. Here we found that our results suggest divergent physical conditions compared to molecular clouds with ongoing starformation. Interestingly, we found a higher than expected level of ionization within the system, a non-uniform behavior of features across distances, a non-uniform size distribution of PAH molecules, as well as a detection of the $\text{H}_2 \text{ S}(0)$ line at larger distances from our illuminating star. All of these suggest that pre-starforming globules do indeed have differing conditions that their later evolutionary stages, and as such are an interesting source of further study.

Our follow-up publication on DC 314.8–5.1, focused on the multi-wavelength properties of the system. We utilized archival as well as dedicated observations with instruments ranging from archival Planck at the low end in microwaves all the way to X-ray with Swift-XRT observations. Here, We confirmed the pre-star forming status of the cloud, through an investigation of the infrared colors of point sources –and complimentary GAIA parallaxes– within the system finding

CHAPTER 5. CONCLUSIONS AND FINAL REMARKS

no potential young stellar objects. We found no pre-main sequence stars in the Swift-XRT data probing down to a luminosity level of $\lesssim 10^{31} \text{erg cm}^{-1}$ in the 0.5–10 keV range. We further investigated the joint Planck, IRAS, and Spitzer satellite data, claiming the presence of a hotter dust component (even up to 300 K) in addition to the dominant 14 K component. Finally, we commented on the discrepancy in mass estimates across instruments/studies as well as the expected γ -ray output of the cloud. All this indicating that DC 314.8–5.1 is, indeed, at a very early evolutionary state and as such constitutes a dense and compact reservoir of cold dust and gas, enabling for a truly unique insight into a primordial form of the ISM.

In particular, we have found indications of some truly interesting phenomenon that begs for further study. In the first instance, we see an indication of the role between the ISM and jet regulation. We will further study this phenomenon through archival infrared spectroscopy of a subset of our sample of compact radio galaxies to probe the connection between jet size and age with the dust properties of the ISM. Specifically, we will look for a relationship between jet age and size with the ionization and size of dust grains present in the host galaxies.

Furthermore, we will continue to study primordial dust clouds (pre-starforming) to deepen our understanding of the chemical processes at play in such systems. We will expand our study of DC 314.8–5.1 to encapsulate a larger sample of pre-starforming molecular clouds, verified as such in a similar manner as above. Through the multi-wavelength study of a large sample of such systems and with dedicated observations of certain phenomenon (such as x-ray absorption, and γ -ray signals) we will constrain the role of cosmic-rays in shaping the internal chemistry, as well as constrain characteristics of these systems across the electromagnetic spectrum.

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