3

The star-forming regions

This thesis is driven by the observational study at infrared and millimeter wavelengths of interstellar molecules belonging to the envelopes of Class 0 and Class I young stellar objects located in three nearby star-forming regions: the Serpens SVS 4 cluster in the Serpens cloud core, the multi-protostellar system IRAS 05417+0907 in the λ Orionis Barnard 35A cloud and the Coronet cluster in Corona Australis. This chapter provides an introduction to the large-scale environments where the targeted sources of Chapters 5, 6 and 7 are currently being formed.

3.1 THE SERPENS MOLECULAR CLOUD COMPLEX

The Serpens Molecular Cloud is one of the most active sites of nearby ongoing star formation. It is located at a distance of 436 ± 9 pc (Gaia DR2;Ortiz-León *et al.*, 2018) and it harbours at least 2000 young stellar objects (Herczeg *et al.*, 2019). The star-formation activity of the cloud was discovered by Strom *et al.* (1974). Since then, the region has been at the center of an extensive multi-wavelength research (e.g. Dame and Thaddeus, 1985; Dame *et al.*, 1987; Eiroa and Casali, 1989; Eiroa *et al.*, 2008 and references therein). The cloud extends for $\approx$500 pc and it is part of the Serpens-Aquila complex (Figure 3.1). Compared to other nearby star-forming regions, it is particularly challenging to characterize as it is observed against the crowded Galactic Plane and it spans over a large range of extinctions.

In the Serpens-Aquila complex there are a number of individual clouds distributed within the Aquila Rift, a suite of dark clouds extending on the sky for over 25° (Cambrésy, 1999; Green *et al.*, 2015). The most studied cloud within the complex is Serpens Main (also referred to as Serpens cloud core and cluster A), where our sources of interest are located (Eiroa *et al.*, 2008) (see Chapter 5). The other star-formation sites are: Serpens Northeast, located at 1° east of Serpens Main (Dunham *et al.*, 2015); W40 and Serpens South, two dense embedded clusters located next to and along a massive filament 3° south of Serpens Main (Gutermuth *et al.*, 2008; Povich *et al.*, 2013; Dunham *et al.*, 2015; Könyves *et al.*, 2015), and Serpens far-South, situated nearby MWC 297 (Bontemps *et al.*, 2010; Dunham *et al.*, 2015; Rumble *et al.*, 2015).

The Serpens cloud core harbours a plethora of deeply embedded protostars (Eiroa *et al.*, 2008 and references therein). The principal Class 0/I

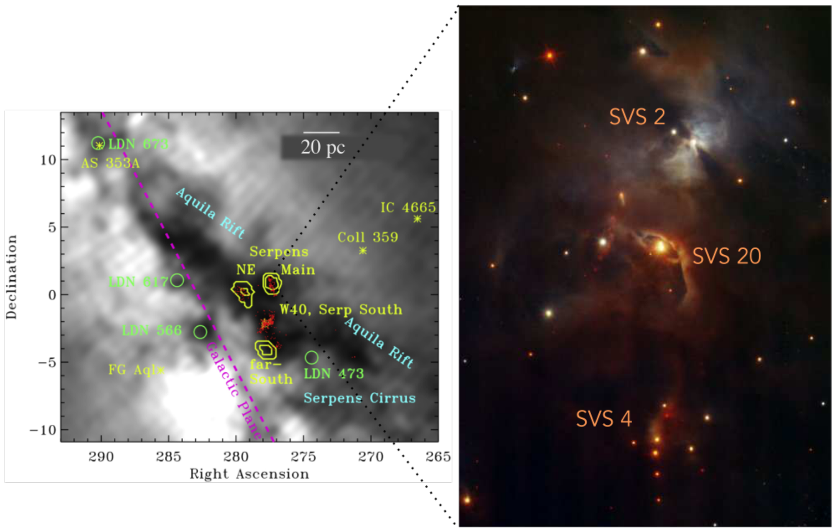

FIGURE 3.1: The Serpens Molecular Cloud Complex. *Left:* An overview of the Serpens-Aquila complex. The Serpens star-forming regions (yellow circles) are interspersed among the dark clouds belonging to the Aquila Rift. The magenta line denotes the Galactic Plane. Credit: Herczeg *et al.* (2019). *Right:* Three-colour image of the Serpens cloud core (also known as Serpens Main). The composite is made from the Very Large Telescope HAWK-I J-, H- and K-bands. The bottom of the image displays the Serpens SVS 4 cluster studied in this thesis. Credit: Eiroa *et al.* (2008).

sources in the core are ten, of which four have been securely classified as Class 0: SMM1, SMM3, SMM4 and S68N (or SMM9) (Hurt and Barsony, 1996). The dynamical structure and physical properties of these four protostars has been studied extensively (e.g., Casali *et al.*, 1993; Davis *et al.*, 1999; Larsson *et al.*, 2000; Harvey *et al.*, 2007; Evans *et al.*, 2009; Kristensen *et al.*, 2010; Tychoniec *et al.*, 2019), revealing stellar multiplicity. For instance, the brightest millimeter source in the core, the Class 0 SMM1 consists of four continuum sources (Choi, 2009; Dionatos *et al.*, 2014; Hull *et al.*, 2017), whereas SMM4 has been resolved into two components (Aso *et al.*, 2018).

The molecular transitions detected towards Serpens Main at infrared, millimeter and submillimeter wavelengths unveil a rich-chemistry in the cloud core (e.g., McMullin *et al.*, 1994; White *et al.*, 1995; McMullin *et al.*, 2000; Kristensen *et al.*, 2010; Öberg *et al.*, 2011c; Dionatos *et al.*, 2013; Martín-Doménech *et al.*, 2019; Bergner *et al.*, 2019), especially towards the innermost regions of the SMM1 envelope.

Chapter 5 of this thesis is centered on Serpens SVS 4, a dense cluster of protostars located in the south-eastern core of Serpens Main near the Class 0 binary SMM4 (Figure 3.1). The cluster counts 11 objects within a region of ≈20 000 AU across, and it is so dense that it was long thought to be a single source, until it was resolved by Eiroa and Casali (1989). The cluster members have low-to-intermediate masses (Pontoppidan *et al.*, 2004) and they have mostly been studied in the near- and mid-infrared spectral domains, especially the two most massive sources SVS 4–5 and SVS 4–9 (Chiar *et al.*, 1994; Pontoppidan *et al.*, 2003a; Boogert *et al.*, 2008; Bottinelli *et al.*, 2010). The cluster currently holds the highest solid-state methanol abundance among low- to intermediate-mass protostars, 28% with respect to water (Pontoppidan *et al.*, 2003b; Pontoppidan *et al.*, 2004), and solid CO_2 abundances $\sim 30 - 50\%$ relative to water (Pontoppidan *et al.*, 2008).

3.2 THE ORION MOLECULAR CLOUD COMPLEX

The Orion Molecular Cloud Complex is the closest site of high-mass star-formation and probably the most studied stellar nursery in our Galaxy and the entire Universe (Menten *et al.*, 2007; Bally, 2008). It extends for $\sim 30°$ on the sky and it harbours a vast number of sub-clouds and stellar groups lying at different distances (Figure 3.2). In the past couple of years, *Gaia* DR2 studies provided more accurate values for the distance to individual parts of the cloud (Zucker *et al.*, 2019; Zucker *et al.*, 2020).

Ongoing star formation in the complex is predominantly concentrated in four regions: Orion A and Orion B, representing the largest sites of star-formation in the main cloud (e.g., Carpenter, 2000; Johnstone *et al.*, 2001; Megeath *et al.*, 2012; Megeath *et al.*, 2016) and home of the Orion Nebulae Cluster (ONC). The youngest populations in Orion A and B form part of the Orion OB1c and OB1d sub-associations, situated at Orion's Sword, $\sim 4°$ south of Orion's Belt (Buckle *et al.*, 2012; Megeath *et al.*, 2012; Polychroni *et al.*, 2013). The third stellar nursery is the σ Orionis region positioned below the eastern side of the Orion's Belt and hosting a stellar population significantly younger compared to the majority of Orion's Belt stars (Walter *et al.*, 1997; Jeffries, 2007; Hernández *et al.*, 2007; Caballero, 2008; Hernández *et al.*, 2014). Finally, the fourth star-forming site is the λ Orionis region, which harbours the sources studied in Chapter 6. It is located in the northernmost part of the complex also known as Orion's head (e.g., Sharpless, 1959; Lada and Black, 1976; Murdin and Penston, 1977; Mathieu, 2008; Bayo *et al.*, 2011; Sahan and Haffner, 2016), at a mean distance of 410 ± 20 pc (Zucker *et al.*, 2019; Zucker *et al.*, 2020).

The λ Orionis region is seen as a ring of dust and gas surrounding a core of OB stars (Figure 3.2) (e.g., Wade, 1957; Maddalena and Morris, 1987; Lang *et al.*, 2000; Dolan and Mathieu, 2002). There are three sub-clouds within the ring: Barnard 30 (B30) and Barnard 35A (B35A) (Murdin and Penston, 1977; Barrado *et al.*, 2018) and Barnard 223 (B23) (Bayo *et al.*, 2011; Bell *et al.*, 2013). It is highly debated whether the latter cloud is associated with the λ Orionis region or only projected in the same portion of the sky, as the radial velocities of the pre-main sequence stars in B223 differ from those in B30 and B35A (Dolan and Mathieu, 2002; Yi *et al.*, 2018). The three clouds exhibit several cold cores, which compared to the cores found in Orion A and B, show the lowest median masses, sizes and gas fraction and the highest dust temperatures (Liu *et al.*, 2016). These factors suggest a negative feedback from the λ Orionis massive star on the formation and evolution of dense cores in the region (Yi *et al.*, 2018; Yi *et al.*, 2021).

Chapter 6 of this thesis studies the young protostellar population of the Barnard 35A cloud (aka B35, BRC18, SFO18, L1594). B35A displays a prominent cometary shape and a bright rim on the western edge (Lada and Black, 1976) (Figure 3.2). The morphology of the cloud, and plausibly the star-formation in its interior, are the result of the interaction between the radiation fields from the nearby OB stars and the expansion of the surrounding HII region Sh2-264 (Sharpless, 1959; Qin and Wu, 2003; Sahan and Haffner, 2016). Objects of interest within the cloud are: the embedded Class I source IRAS 05417+0907 ($L = 6L_{\odot}$; Sugitani *et al.*, 1991; Morgan

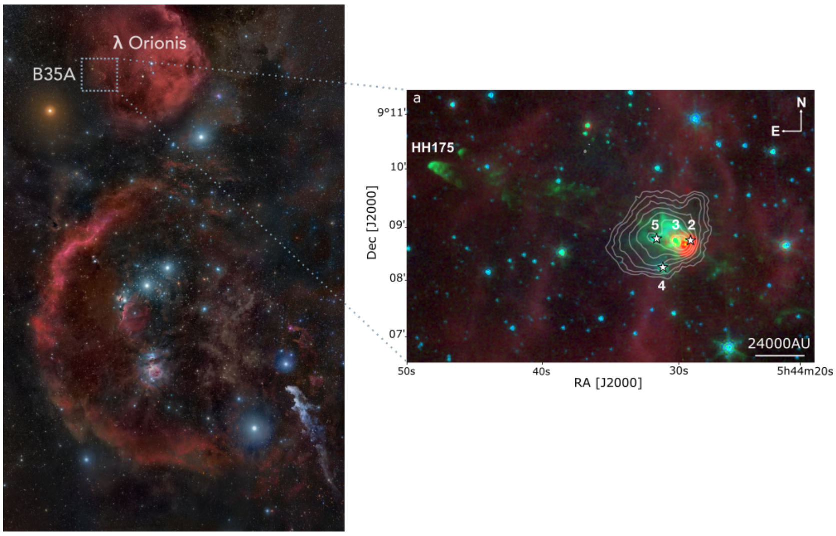

FIGURE 3.2: The Orion Molecular Cloud Complex. *Left:* An overview of the Orion Cloud Complex. The Barnard 35A cloud (dotted rectangle) is located to the east of the λ Orionis star Credit: R. B. Andreo. *Right:* Three-colour image of the Barnard 35A cloud. The composite is made from the *Spitzer* IRAC 3.6 μm (blue), 4.5 μm (green) and MIPS 24.0 μm (red) bands. A SCUBA–2 850 μm map (Reipurth and Friberg, 2021) is overlaid on the composite. For more details on this figure please refer to Chapter 6).

et al., 2008) for long thought to be a single source, but forming a system composed by at least four objects (Connelley *et al.*, 2008; Reipurth and Friberg, 2021); the FU Orionis star situated to the south-eastern end of the cloud enclosed in a large reflection nebula (Herbig, 1966), and the giant Herbig-Haro object HH175 (Myers *et al.*, 1988; Qin and Wu, 2003; Craigon, 2015; Reipurth, 2000) emanated from the IRAS 05417+0907 multiple system and crossing the cloud in the eastern-western direction for ~1.6 pc at the cloud's estimated distance (Reipurth and Friberg, 2021).

The large-scale morphology and chemical inventory of B35A have been studied at millimeter and submillimeter wavelengths (De Vries *et al.*, 2002; Craigon, 2015; Kim *et al.*, 2020; Reipurth and Friberg, 2021; Yi *et al.*, 2021) and in the optical/near-infrared (Noble, 2011; Noble *et al.*, 2013; Noble *et al.*, 2017; Suutarinen, 2015a; Reipurth and Friberg, 2021).

3.3 THE CORONA AUSTRALIS MOLECULAR CLOUD COMPLEX

The Corona Australis Molecular Cloud Complex (CrA) is one of the nearest star-forming regions disclosing a wealth of young embedded objects (Peterson *et al.*, 2011). It is located at a distance of 149.4 ± 0.4 pc (*Gaia*-DR2; Galli *et al.*, 2020) and it extends for over 5° on the sky. The study of Corona Australis, and specifically of its young stellar population, was initiated by Herbig (1960) who discovered two variable young stars, R CrA and T CrA, in the region of the cloud characterized by the highest extinction. The follow-up works made Corona Australis one of the best targets for star-formation studies (e.g., Taylor and Storey, 1984; Knacke *et al.*, 1973; Neuhäuser *et al.*, 2000; Nutter *et al.*, 2005; Forbrich *et al.*, 2007; Peterson *et al.*, 2011).

Corona Australis possesses a characteristic elongated "head-tail" structure (Figure 3.3). The "head" region, also referred to as the "Coronet", is where

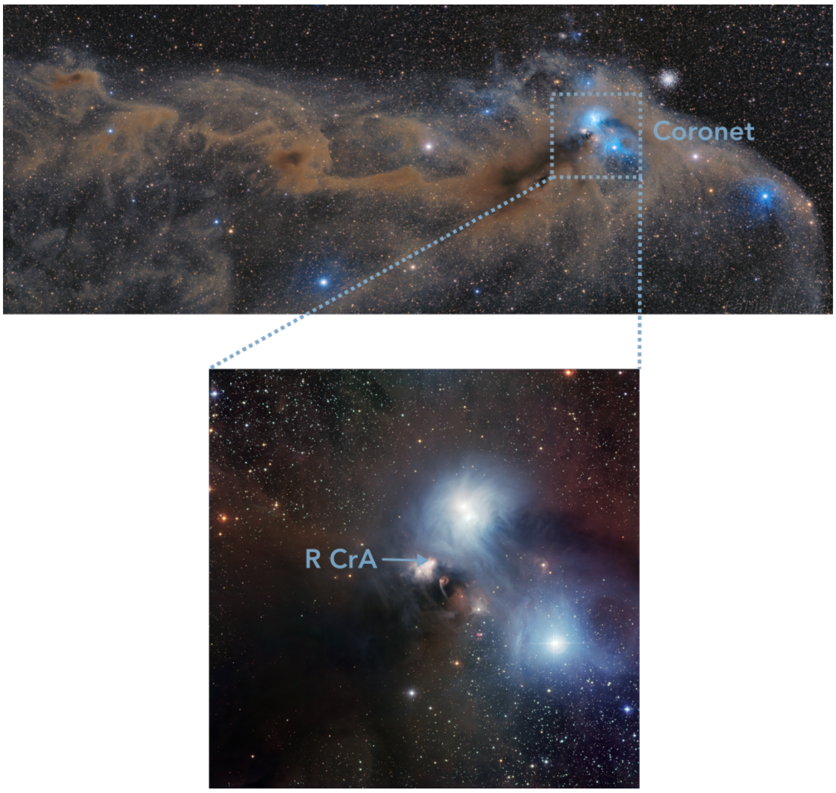

FIGURE 3.3: The Corona Australis Molecular Cloud Complex. *Top:* An overview of the Corona Australis Cloud Complex. The Coronet cluster (dotted rectangle) represents the densest region of the cloud. It harbours the Herbig Ae/Be star R CrA and several Class 0/I young stellar objects Credit: F. Neyer. *Bottom:* Three-colour image of the Coronet cluster. The composite is made from MPG/ESO telescope Wide Field Imager 456 nm (blue), 539 nm (green) and 651 nm bands. Credit: ESO.

most of the young stellar population (Class 0/I) is concentrated (Taylor and Storey, 1984; Forbrich *et al.*, 2007; Forbrich and Preibisch, 2007). The Coronet is the targeted region described in Chapter 7. The most recent membership analysis study of Corona Australis detected a total of 262 young stellar objects, of which the vast majority are Class II/III sources (Galli *et al.*, 2020). The census also reports the existence of a large population of more evolved YSOs located "off cloud", in the northern region of the complex (Galli *et al.*, 2020). The number of youngest objects (Class 0/I) is not well constrained due to the high extinction of the densest clouds and especially of the Coronet region (Alves *et al.*, 2014; Galli *et al.*, 2020).

Five dark clouds have been detected in CrA from the extinction map of Rossano (1978). These are named A to E, starting from the Coronet (CrA-A) in the eastern side of the cloud to the west-southern end (Figure 3.3). The location of the dense cores in the complex is well correlated with the spatial distribution of the filamentary structure where the clouds are (Bresnahan *et al.*, 2018). Notably, only low-mass starless cores were identified further away from filaments, whereas all the more massive cores were detected along filaments inside the clouds or in their vicinity (Bresnahan *et al.*, 2018).

Among the five dark clouds, the most studied is the Coronet which harbours the Class 0/I sources targeted in Chapter 7. This site is responsible for the majority of the dynamical activity in the entire complex. Beside hosting the variable Herbig Ae/Be star R CrA, it is home of the T Tauri star T CrA, located to the south-east of R CrA (Taylor and Storey, 1984). The region among the two variable stars, also known as the IRS7 region, harbours a pre-stellar core, SMM1A, and a suite of Class I (or lower) young stellar objects (e.g., Brown, 1987; Nutter *et al.*, 2005; Groppi *et al.*, 2007; Chen and Arce, 2010; Peterson *et al.*, 2011). The wealth of arcs and clumps in the area, identified as Herbig-Haro objects, corroborates the presence of young stellar objects belonging to the earliest classes (Strom *et al.*, 1974; Reipurth, 2000).

A number of multi-wavelength studies has been carried out towards the Coronet, aiming at investigating the effect of external irradiation of R CrA onto the physical and chemical evolution of the protostars in the region. Most observations, including unbiased surveys, were conducted at millimeter/submillimeter wavelengths (e.g., Schöier *et al.*, 2006; Lindberg and Jørgensen, 2012; Watanabe *et al.*, 2012; Lindberg *et al.*, 2015; Lindberg *et al.*, 2017) and suggest that the Herbig Ae/Be star R CrA influences the region by increasing the temperature of the molecular gas and by favouring the formation of photon-dominated regions through irradiation. The mid-infrared spectra of a handful of objects in the Coronet present ice features attributable to H_2O, CO_2, CH_3OH, and plausibly ammonium ion (Boogert *et al.*, 2008; Pontoppidan *et al.*, 2008; Bottinelli *et al.*, 2010).

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