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Star Formation in Sagittarius: The Lynds 291 Cloud

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Abstract. The Lynds 291 cloud in Sagittarius is a giant molecular cloud with approximate dimensions 20 pc × 80 pc located at a distance of approximately 1700 pc. The northern part of the cloud is dominated by the HII region IC 1284 and the two reflection nebulae NGC 6589 and NGC 6595. The southwestern edge of the cloud consists of a high extinction ridge with numerous dense cores that are being compressed by an expanding HI bubble energized by OB stars and possibly several past supernova explosions. Star formation is taking place all along the ridge. A particularly well studied source is IRAS 18162–2048, which drives the very luminous Herbig-Haro objects HH 80/81, a highly collimated radio continuum jet, and a massive molecular outflow.

1. Overview

The Lynds 291 cloud forms a major molecular cloud complex in Sagittarius, located around the Galactic coordinates $l \sim 11°$, $b \sim -2°$, and stretching across 4 square degrees (see Figures 1 and 2). Lynds (1962) listed a number of clouds in this region (L291, 306, 314, 315, 322), which are not all obvious to identify on modern sky maps, so we use L291 here to designate the entire cloud complex. In the new cloud atlas by Dobashi et al. (2005), L291 is designated TGU 116, with 8 cores, labeled P1-P8.

To the north, the region is dominated by three prominent nebulae, IC 1284, NGC 6589, and NGC 6595, seen in Figure 3. IC 1284 is an HII region, 15 arcmin in diameter, which has in its center the 7th magnitude double star HD 167815 with spectral types B1/B2 III (Houk & Smith-Moore 1988). IC 1284 was discovered by Barnard (1892), and is also known as S37 (Sharpless 1959) and W34 (Westerhout 1958). It is part of a larger ionized region known as Gum 78 (Gum 1955) and RCW 153 (Rodgers, Campbell, & Whiteoak 1960). The two smaller nebulae to the south-west, NGC 6589 and 6595, are illuminated by the B2 II star HD 167638 and the B5 binary HD 313094 + HD 313095, respectively. Quite a bit of confusion has reigned over the identification of these two nebulae. NGC 6589 was found by Swift (1886), who gave an incorrect position that was corrected by Barnard (1892). NGC 6595 was originally found by John Herschel in 1830 and listed as h2002 (Herschel 1864). It was re-discovered by

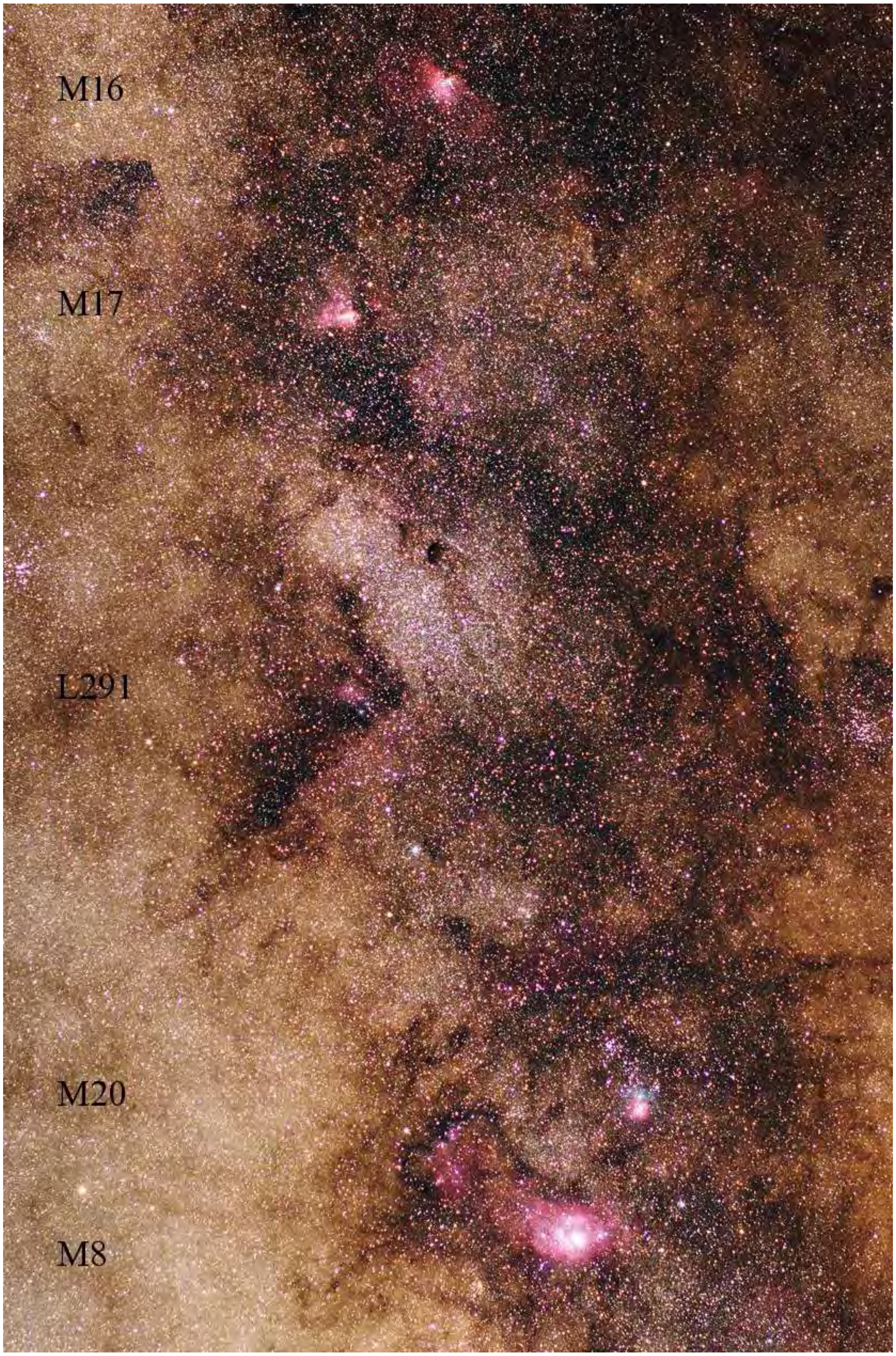

Figure 1. The L291 molecular cloud in context. The field stretches along the Galactic plane from M16 to M8. Courtesy Manuel Jung.

Swift, but due to incorrect coordinates it was given the separate number NGC 6590 by Dreyer (1888). NGC 6595 is thus the correct identification for this object (for unknown reasons, the NGC lists 6595 as a cluster, but there is no cluster in this region, only the central binary). NGC 6589 and 6595 are also known as the reflection nebulae vdB 118 and 119, respectively (van den Bergh 1966) and the bright nebulae LBN 46 and 43, respectively (Lynds 1965).

Figure 2. The L291 molecular cloud as seen in a wide-field ($2^\circ \times 2^\circ 45'$) H$\alpha$ emission image. Courtesy John P. Gleason.

The north-west corner of the L291 cloud is abutting one of the richest patches of the Milky Way, easily visible to the naked eye and known as M24 or popularly as the “Sagittarius Star Cloud”.

The distance to the L291 complex is not determined with high accuracy. Racine (1968) estimated the distance moduli of the stars in the reflection nebulae vdB 118 and 119, and suggested a distance of 1.6 kpc. Rodríguez et al. (1980) used CO velocities and a Galactic rotation model to estimate a kinematic distance of 1.7 kpc. Evans et al. (1982) adopted a distance of 1.5 kpc, and Saito et al. (1999) suggested a kinematic distance of 1.8 kpc. The L291 cloud is flanked to the southwest by the Sgr OB7 association, which Saito et al. (1999) argue interacts with the cloud (see Section 2), and which Humphreys (1978) suggests is at a distance of 1.75 kpc. To the northwest of L291 is located the Sgr OB4 association, which Humphreys (1978) suggests is at a distance of 2.4 kpc, but there are no studies which indicate that the association interacts with the L291 cloud. In the following, we use a distance of 1.7 kpc as a reasonable compromise and because this distance is the one most commonly used in the literature, however its uncertainty should be kept in mind.

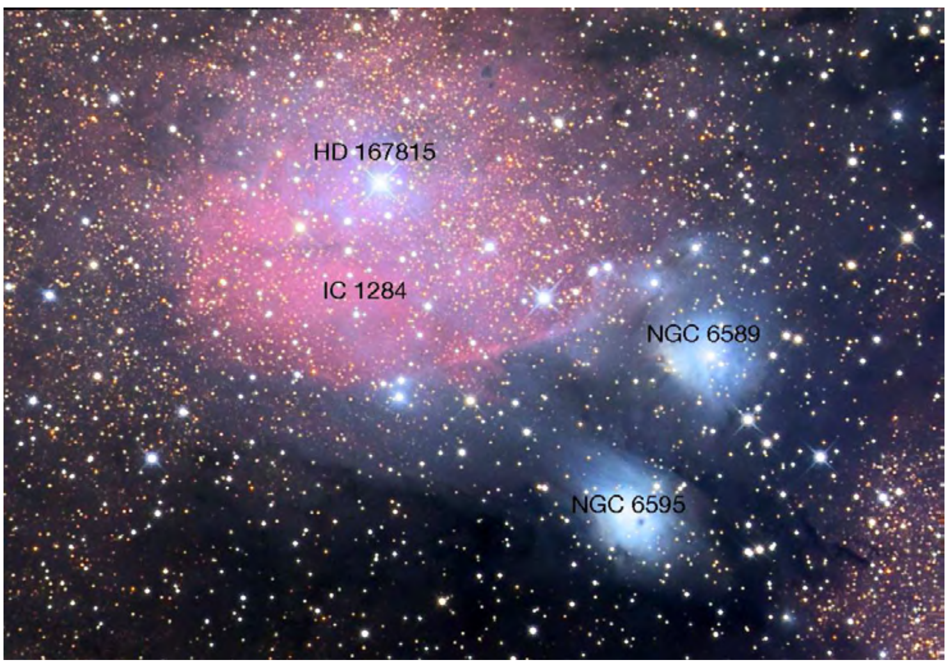

Figure 3. The northern part of the L291 cloud is dominated by the HII region IC 1284 and the two reflection nebulae NGC 6589 and NGC 6595. Courtesy Daniel Verschatse.

2. The Molecular Cloud Complex and the Atomic and Ionized Gas

The IC 1284 (S37) region was observed in the radio continuum by Altenhoff et al. (1970) and Goss & Day (1970), and their results imply a flux of Lyman continuum photons larger than what the central object HD 167815 can produce, suggesting that more sources, possibly partly embedded, could be ionizing the gas. The region around IC 1284 as well as around NGC 6589 and 6595 was mapped by Evans et al. (1982) in CO, ^{13}CO, H_2CO, and HCN, which revealed a large molecular cloud with two cores.

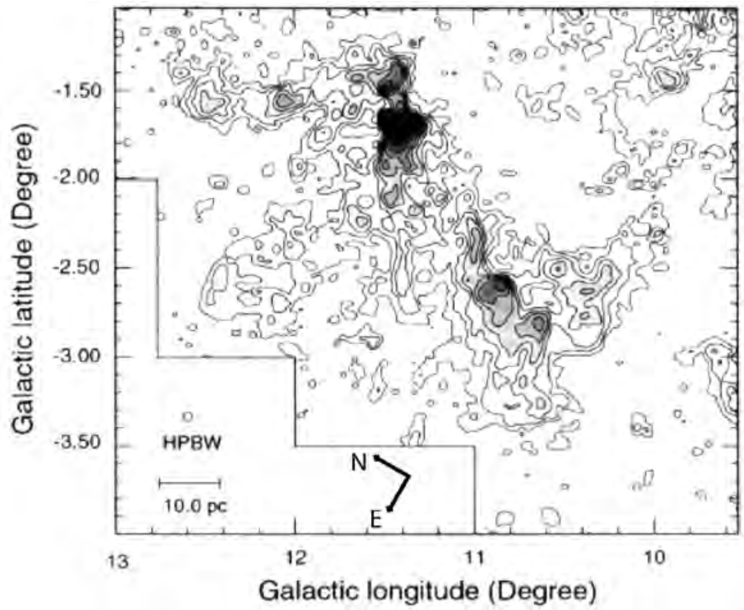

Figure 4. An integrated intensity map of ^{12}CO (J=1-0) of L291 in Galactic coordinates. The integrated range is 0.0 km/sec $< V_{lsr} <$ 20.0 km/sec. From Saito et al. (1999).

The entire L291 cloud was mapped in ^{12}CO, ^{13}CO, and $C^{18}O$ by Saito et al. (1999) in a comprehensive millimeter wavelength study with the Nanten telescope. They find that L291 comprises a giant molecular cloud with approximate dimensions of $\sim$80 pc $\times$ $\sim$20 pc and a mass exceeding 10^5 $M_\odot$. The denser gas is concentrated in a major ridge, seen in Figure 4, which corresponds to the well defined edge of the L291 complex facing towards the south-west in the optical image in Figure 2. A faint, very extended HII region, called S35, is located all along this ridge, and is excited by about 20 massive stars with spectral types earlier than B4, also known as the Sgr OB7 association (Humphreys 1978). 21 cm maps show that S35 coincides with a large HI hole about 110 pc in diameter that is surrounded by an expanding shell with an expansion velocity of $\sim$8 km/sec (Hartmann & Burton 1997). Saito et al. (1999) suggest that this expansion is partly due to the ionizing sources of the HII region, and partly results from several supernova explosions over the last $\sim 3 \times 10^6$ yr. The strong density gradient seen in the L291 molecular ridge is likely the result of compression by the expanding shell. This has resulted in recent very active star formation in L291, as discussed in Sections 3 and 4.

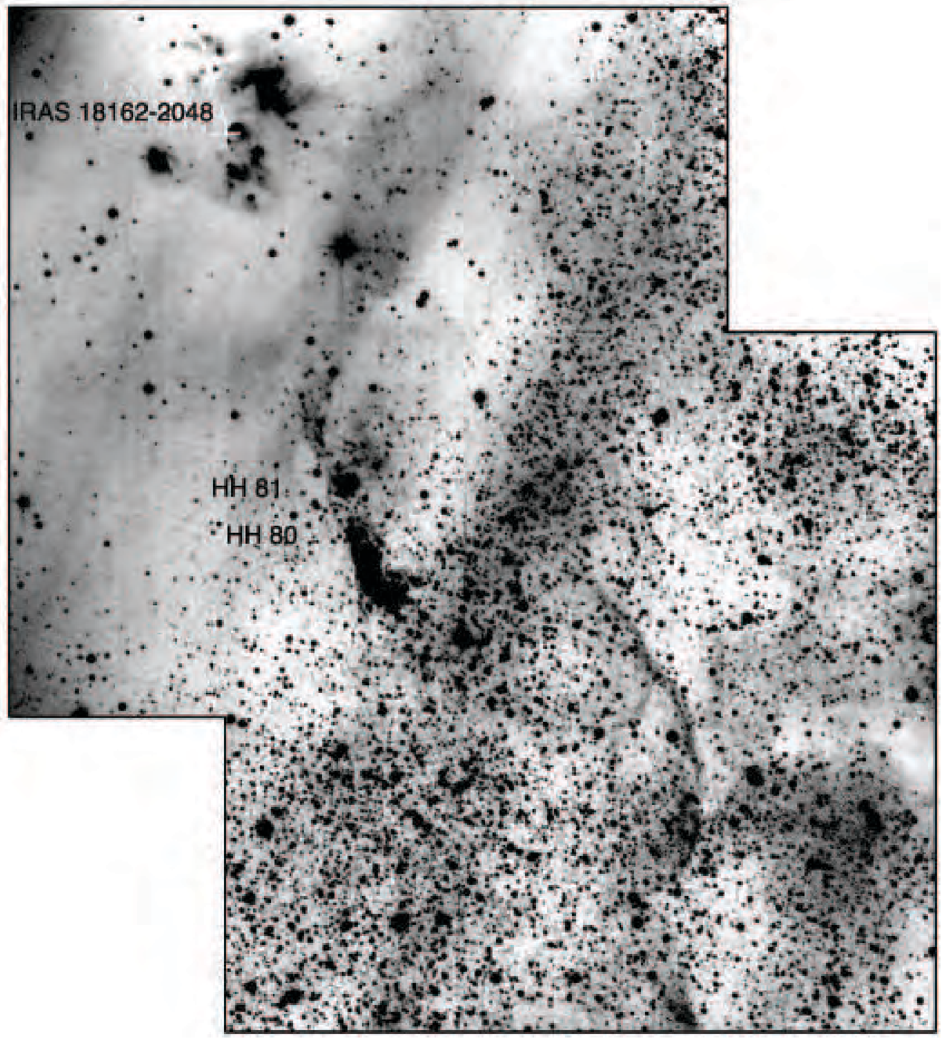

Figure 5. An Hα image mosaic of the HH 80/81 flow. The cross marks the driving source IRAS 18162−2048, HH 80/81 are the two nebulous objects left of center, and a partial giant bow shock is seen to the lower right. From Heathcote, Reipurth, & Raga (1998).

3. IRAS 18162−2048 and HH 80/81

Attention was drawn to the L291 cloud by the discovery of two small nebulae, now known as GGD 27 and 28, by Gyulbudaghian, Glushkov, & Denisyuk (1978). At the time they were thought to be new Herbig-Haro objects, but they turn out to be compact reflection nebulae (Hartigan & Lada 1985). Precise coordinates for the objects are given by Rodríguez et al. (1980). In a study of the L291 cloud, Reipurth & Graham (1988) discovered two very bright Herbig-Haro objects, HH 80 and 81, which, given their distance of 1.7 kpc, turn out to be the two intrinsically most luminous HH objects known. HH 80 has a bright core and is associated with a cluster of HH knots, whereas

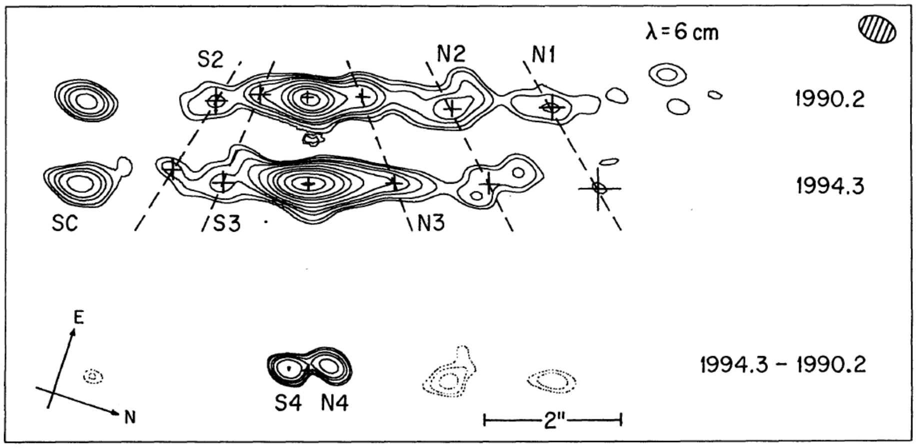

Figure 6. Two epochs of 6 cm radio continuum maps of the HH 80/81 radio jet showing the high collimation of the jet and the proper motions of the knots, corresponding to tangential velocities between 600 and 1400 km/sec. Difference images show that two new knots were formed around the source between the two epochs. From Martí, Rodríguez, & Reipurth (1995).

HH 81 is more isolated. Heathcote, Reipurth, & Raga (1998) present detailed CCD images, both groundbased and from the HST, together with high-resolution spectroscopy and a proper motion study. Very high shock velocities, in excess of 600 km/sec, are implied by the observed kinematics, and this was corroborated by the detection of both HH objects in X-rays (Pravdo, Tsuboi, & Maeda 2004). The HH 80/81 flow is very well collimated from the source and out to the HH objects, but then abruptly widens into a network of faint shock excited streamers, terminating in a giant bow shock (see Figure 5). This morphology may arise when fast, very hot bullets like HH 80 and HH 81 violently expand as they escape from the cloud into low pressure surroundings. A line drawn through the objects intersects the 16000 $L_\odot$ embedded IRAS source 18162–2048, which is the driving source. Rodríguez et al. (1980) detected a compact HII region there, as well as OH and H_2O masers, and the source was detected at 1300 μm by Reipurth et al. (1993). Rodríguez & Reipurth (1989) detected both HH objects in the radio continuum and found the source to be elongated towards the HH objects. Higher resolution observations at 6 cm and 3.6 cm by Martí, Rodríguez, & Reipurth (1993) revealed a highly collimated bipolar radio continuum jet emanating from the source. Large proper motions and ejection of new knots in the radio jet were reported by Martí, Rodríguez, & Reipurth (1995, 1998), see Figure 6. On the opposite side of the source with respect to HH 80/81 they found a resolved object, HH 80N, with the same negative spectral index as HH 80 and 81. Far-infrared spectroscopy of HH 80N with ISO confirmed that it is an embedded HH object (Molinari, Noriega-Crespo, & Spinoglio 2001). Ammonia was found downstream from HH 80N by Girart et al. (1994), and this region was studied further in HCO^+ and ^{13}CO by Girart, Estalella, & Ho (1998), and Girart et al. (2001) found evidence for star formation near HH 80N. Gómez, Rodríguez, & Martí (1995) concluded that the HH 80/81 thermal radio jet and the nearby H_2O maser are driven by different sources. Further observations of masers in the region were presented by Martí et al. (1999), Val'tts et al. (2000), Furuya et al.

(2003), and Kurtz & Hofner (2005). Next to the source one finds the small reflection nebula, GGD 27, and Yamashita et al. (1987) noted a large infrared reflection nebula, coincident with a major and very massive molecular outflow (Yamashita et al. 1989, Benedettini et al. 2004, Wu et al. 2005). A dense CS disk was found around the HH driving source perpendicular to the outflow direction by Yamashita et al. (1990), and aperture synthesis observations by Yamashita et al. (1991) revealed three unresolved peaks. Further high-resolution molecular line observations of the source region were discussed by Gómez et al. (2003). Aspin et al. (1991) performed near-infrared imaging and spectroscopy of the source region, and Aspin & Geballe (1992) did mid-infrared spectroscopy, finding evidence for a cluster of sources. Similarly, Pravdo et al. (2004) found a cluster of X-ray sources around the jet source. Aspin (1994) found extended infrared CO emission around the source. Aspin et al. (1994) detected the source with 4.7 μm imaging. Stecklum et al. (1997) presented high resolution imaging at several infrared wavelengths. McCutcheon et al. (1995) presented maps at 450, 800 and 1100 μm, and Chini et al. (1997) at 1300 μm. Other 450 and 850 μm maps were obtained by Thompson et al. (2006). Greaves, Holland, & Ward-Thompson (1997) presented 800 μm polarimetry of the source. Coordinates for the known HH objects in L291 are given in Table 1.

Table 1. Herbig-Haro Objects in Lynds 291

ID	α_{2000}	δ_{2000}
HH 80	18 19 06.1	–20 51 50
HH 80N[a]	18 19 19.7	–20 41 35
HH 81	18 19 06.6	–20 51 07
HH 180	18 17 23.1	–19 51 46

a: Radio continuum source presumed to be an embedded HH object

4. IRAS Sources and Hα Emission Stars in L291

While IRAS 18162–2048 has become very well known because of its collimated outflow, it is not the only massive star that is forming in L291. In their millimeter survey, Saito et al. (1999) identified 18 $C^{18}O$ clumps, of which about half were found to be associated with IRAS sources with the rising energy distributions characteristic of Class I sources. These IRAS sources are high luminosity sources indicating that they represent massive star formation events, see Table 2. Saito et al. (1999) found that 5 of these IRAS sources are driving molecular outflows.

Thé (1966) carried out a survey for Hα emission line stars in a large region of Sagittarius including the L291 cloud. Table 3 contains a list of the 7 emission line stars that are located within the boundaries of the L291 cloud.

We have carried out a deeper survey of Hα emission stars in L291 with the Curtis Schmidt telescope at CTIO, the results of which were never published, but the 15 emission-line stars that we identified are listed here in Table 4. All stars exhibit a fairly strong Hα emission line. We obtained spectra at CTIO and ESO of all these stars, and we briefly comment on the individual stars below.

Table 2. IRAS Sources associated with $C^{18}O$ Cores in L291 (from Saito et al. 1999)[a]

IRAS #	α_{2000}	δ_{2000}	12μm	25μm	60μm	100μm	L($L_\odot$)[b]	Notes
18162–2048	18 19 11.8	–20 47 35	25.73	346.70	2771.0	3709.0	25000	HH80/81
18155–2031	18 18 32.6	–20 30 31	0.93	2.16	17.8	60.8		
18150–2016	18 17 59.8	–20 14 58	0.89	1.53	29.6	94.8		outflow
18138–1954	18 16 50.4	–19 53 24	10.29	20.43	188.8	1641.0	6100	
18139–1952	18 16 57.1	–19 51 08	11.28	154.00	1122.0	1730.0	11000	outflow
18128–1943	18 15 48.1	–19 42 18	1.83	2.36	14.5	118.5		outflow
18134–1942	18 16 21.6	–19 41 31	10.34	74.61	767.8	1548.0	8400	outflow
18128–1929	18 15 48.3	–19 28 28	4.76	6.21	6.5	227.2	840	
18132–1926	18 16 13.2	–19 25 38	1.14	1.27	10.7	484.9	1600	

a: Fluxes in columns 4-7 are given in Jy
b: The luminosity is estimated only for sources with high IRAS data quality

Table 3. Hα Emission Stars in L291 (Thé 1966)[a]

ID	α_{2000}	δ_{2000}	V mag
THA34-35	18 16 15.2	–19 25 33	13.7
THA34-36	18 17 08.1	–18 59 48	14.5
THA34-37	18 17 10.7	–19 42 12	13.5
THA34-38	18 18 39.9	–19 31 31	13.0
THA34-40	18 19 39.2	–20 39 35	11.8
THA34-41	18 20 14.5	–20 11 47	10.7
THA34-42	18 20 29.6	–19 58 23	13.7

a: Coordinates and V mags from Simbad

Table 4. New Hα Emission Stars in Lynds 291

Star	α_{2000}	δ_{2000}	B[a]	R[a]	J[b]	H[b]	K[b]
ESO Hα 285	18 10 52.92	–20 14 31.3	15.2	16.1	13.128	12.314	11.665
ESO Hα 286	18 11 14.25	–20 27 54.1	13.3	15.8	10.426	9.672	9.025
ESO Hα 287	18 11 36.14	–20 21 42.7	14.7	16.4	12.274	11.107	10.122
ESO Hα 288	18 11 49.79	–20 17 51.1	13.7	15.7	11.814	10.155	8.774
ESO Hα 289	18 12 16.88	–20 11 04.3	14.4	16.7	11.499	10.868	10.373
ESO Hα 290	18 15 33.14	–19 44 03.1	15.6	19.3	11.341	10.236	9.458
ESO Hα 291	18 16 02.20	–18 09 52.8	14.3	16.3	11.752	11.401	11.064
ESO Hα 292	18 16 06.80	–18 04 05.5	14.6	15.9	12.143	11.681	11.186
ESO Hα 293	18 16 14.57	–19 25 40.5	13.3	14.4	11.087	10.101	9.151
ESO Hα 294	18 16 28.26	–19 24 28.2	14.4	16.0	12.320	11.824	11.522
ESO Hα 295	18 16 30.05	–19 21 10.1	15.1	16.7	12.402	11.521	11.025
ESO Hα 296	18 16 56.33	–18 00 37.8	13.3	16.6	11.166	9.952	9.070
ESO Hα 297	18 18 40.92	–20 47 29.1	14.2	15.8	12.838	12.228	12.042
ESO Hα 298	18 18 58.29	–20 42 10.8	15.9	17.2	12.789	11.722	10.964
ESO Hα 299	18 19 58.09	–20 28 59.2	12.9	14.7	11.460	11.133	10.872

a: From the Digitized Sky Survey
b: From 2MASS

ESO Hα 285 – The star has spectral type K0, and is probably a T Tauri star.

ESO Hα 286 – Both Hα and Hβ are in emission, and the higher Balmer lines are in faint absorption on a very red continuum, the OI 7776 line is in emission, and there are strong absorptions from diffuse interstellar bands. The spectral type is B:.

ESO Hα 287 – Only Hα is seen in emission, the other Balmer lines are in absorption, and the spectral type is around B8.

ESO Hα 288 – Only Hα is in emission, the other Balmer lines are in absorption, there are strong diffuse interstellar bands, and the spectral type is around A0.

ESO Hα 289 – Only Hα is in emission, the spectrum, which is quite noisy, shows a featureless red continuum with diffuse interstellar bands.

ESO Hα 290 – All Balmer lines are strongly in emission, together with Ca II H and K, and lines of Fe II, as well as the Sodium doublet. The continuum shows no absorption features.

ESO Hα 291 – Hα is in emission and the Hβ absorption line has a weak central emission core, the higher Balmer lines are in absorption. This spectrum extends further into the red and exhibits the Ca II IR triplet and O I 8446 emission of similar strength. Strong diffuse interstellar bands are visible. The spectral type is around A0, and this probably is a Herbig Ae/Be star.

ESO Hα 292 – Only Hα is in emission, all other Balmer lines are in absorption. The spectrum extends further into the red and exhibits CaII IR triplet and OI 8446 emission of similar strength. Strong diffuse interstellar bands are visible. The spectral type is around A0, and this probably is a Herbig Ae/Be star.

ESO Hα 293 – Hα is in emission, the Hβ absorption line has a central emission core, while the higher Balmer lines are in absorption. There are faint diffuse interstellar bands, and the spectral type is approximately B8. This star is about 7 arcsec from the position for THA34-35, and it seems likely that they could be the same star considering the positional uncertainty of the older data.

ESO Hα 294 – Hα is in emission, the Hβ line is in absorption but may be partly filled in, and the higher Balmer lines are all in absorption. Diffuse interstellar bands are present, and the spectral type is around B3.

ESO Hα 295 – The Hα and Hβ lines are in emission, the spectrum shows strong MgH band absorption, G band absorption, and strong Na D absorption. The spectral type is around K5, and the star is likely a T Tauri star.

ESO Hα 296 – All Balmer lines are strongly in emission, as are the CaII H and K lines. A number of FeII lines are also in emission, as well as HeI and OI 7776. The spectrum extends further to the red and exhibits the CaII IR triplet very strongly in emission, also the OI 8446 and Paschen lines are seen in emission. There is faint emission of the forbidden line [O I] 6300, and Na D is in absorption. TiO bands are present, indicating a spectral type around M2. Photospheric lines are veiled. This is clearly a classical T Tauri star. The star is not in L291 but is projected onto the edge of the globule B92, located to the northwest of L291 (see the chapter on Bok globules).

ESO Hα 297 – Hα is in emission, and Hβ is in faint emission. The spectrum shows strong MgH band absorption, strong Na D absorption, a strong G band, and the spectral type is around K3. This appears to be a T Tauri star.

ESO Hα 298 – All the Balmer lines are strongly in emission, as are CaII H and K, a number of FeII lines, and OI 7776. The spectrum is so heavily veiled that no absorption features are visible.

ESO Hα 299 – Hα is in emission, Hβ is in absorption but partly filled in, while the higher Balmer lines are in absorption. Diffuse interstellar bands are present. The spectral type is around B8.

Some of these stars represent part of the young low-mass population that is present in the L291 cloud, but it is evident that the region needs and deserves a much more detailed study to map out its full star formation history.

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