

New detection of near-infrared H₂ line emission in AFGL 5157

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Abstract. Narrow-band H₂ $v = 1-0$ S(1) and broad-band K' imaging observations towards AFGL 5157 revealed a number of new H₂ knots associated with the NH₃ core in the region, implying that the multiple H₂ outflows are driven by a cluster of embedded point sources in the core. The shell around the infrared cluster is more clearly seen than before, showing a few of newly detected ridge-like features. A string of H₂ knots newly revealed along one lobe of the known CO outflow suggests a parsec-scaled jet emanating from a young source in the core. These H₂ outflows and jet, together with the known compact H II region, radio continuum source, and H₂O masers further imply an extremely embedded cluster containing massive stars within it. The evidence shows that the massive young stars within the cluster are in a strong outflow stage of evolution, and together with the nearby infrared cluster in NGC 1985, further confirms that star forming process propagates from the west to the east in AFGL 5157. The two types of H₂ line emission, knots and shell, may be indicators of two different stages of star formation in clusters: the shocked H₂ knots are driven by the young stellar sources embraced in the younger cluster, while the diffuse shell-like structure comes from UV photons of relatively evolved cluster. The near-infrared nebula in AFGL 5157 is found to be only associated with the evolved cluster but not observed in the embedded cluster.

Key words. ISM: lines and bands – ISM: individual objects: AFGL 5157 – ISM: jets and outflows – stars: formation

1. Introduction

The detection of the near-infrared H₂ $v = 1-0$ S(1) (2.12 μ m) line emission is an effective census in the study of star formation. The emission usually appears as two types, shocked-driven knot and diffuse emission. The diffuse emission is excited by the ultraviolet pumped fluorescence, which causes such emission lines in the infrared (Tielens & Hollenbach 1985; Gatley et al. 1987).

Signs of outflow activities have been searched for with CO (115 GHz), H₂ (2.12 μ m), and [SII] (6717/30 Å) lines for star forming regions, in which crowded high-mass stars usually are still embedded in the dense molecular clouds. The often-used CO and [SII] lines suffer from poor spatial resolution (>15'') and heavy extinction, respectively, while the H₂ line is able to delineate the outflow/jet structures through extinction with a high spatial resolution. The detection of shocked H₂ flows in heavily obscured regions could be suggestive of a relatively strong outflow activity in the recent past. Moreover, one can hope to detect the flows from the sources invisible even at near-infrared

wavelengths; among such sources one can find the clues about the Class 0 young stellar objects (YSOs), only a few of which are currently known (Park & Kenyon 2002). The large-scale diffuse H₂ emission is a common phenomenon appearing at the outskirts of the young clusters, being “visible” in the infrared (Gatley et al. 1987; Chen et al. 1999; Yao et al. 2000). This diffuse emission usually occurs on the surface of the remaining molecular material illuminated by young massive stars (Gatley et al. 1987). For example, UV-pumped fluorescence is found to come from a circumstellar thin shell in the reflection nebula NGC 2023 (Gatley et al. 1987), which lies just outside the nebula of dust grains proposed by Sellgren (1984) on the basis of continuum observations. The appearance of arc, shell, and filament structures seem to be related to different evolutionary stages of infrared clusters (Chen 2001).

AFGL 5157 is one of the active star formation sites under close investigation for the past decade (Chen et al. 1999; Hodapp 1994; Torrelles et al. 1992a,b; Henning et al. 1992; Pastor et al. 1991). There is a bipolar CO outflow extended in the E–W direction (Snell et al. 1988) and centered on the dense molecular core. The molecular core, as traced by CS and NH₃ lines, elongates in the N–S direction (Verdes-Montenegro et al. 1989; Pastor et al. 1991; Torrelles et al. 1992b). Torrelles et al. (1992b) observed an H II region and some H₂O masers in

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the core. Chen et al. (1999) found an infrared cluster $\sim 1'$ S–W of the core. The cluster produces a diffuse H₂ shell structure through UV fluorescence, which is morphologically coincident with the infrared nebula. Several H₂ knots (Chen et al. 1999) are observed around the periphery of the dense NH₃ core, suggestive of multiple outflow activity.

This paper presents our new NIR observations toward AFGL 5157. The observations reveal several new H₂ knots around the core in addition to those detected previously (Torrelles et al. 1992a; Chen et al. 1999), a parsec-scaled H₂ jet tracing back to the NH₃ core, and the fine shell structure surrounding the infrared cluster. We discuss the two forms of H₂ line emission related to the evolutionary stages of a cluster which is believed to be hidden deeply in the NH₃ core, and the infrared cluster associated with NGC 1985. In addition, some features of infrared nebula will be described.

2. Observations and data reduction

AFGL 5157 were imaged with the 1.88 m telescope of Okayama Astronomical Observatory, Japan, using OASIS (Yamashita et al. 1995; Okumura et al. 2000) on November 20 1999 and November 17 2000. OASIS is a NIR camera and spectrometer equipped with a NICMOS3 array, having a field of view of 4.2×4.2 with a plate scale of 0.97 pixel^{-1} . On November 20 1999, ten dithered images were obtained in the H₂ (2.12 μm) and *K'* (2.16 μm) bands, with the total integration times of 10 min and 2 min, respectively. On 2000 November 17, twelve and ten dithered images were observed again in the H₂ and *K'* bands with the total integration times of 12 min and 100 s, respectively.

The images were processed with the standard IRAF package. Each image was dark-subtracted, field-flattened, and background-subtracted. The flat was constructed by two sets of dome flat frames taken by an illuminating lamp being on and off. The background frames were obtained by medium filtering of the flat-fielded data frames. The reduced image in each band was registered and aligned using common stars and then combined into a final image. The *FWHM* of the seeing disk was measured to be ~ 1.6 .

To obtain an H₂ line emission image, we subtract a continuum image from the observed H₂ image. A weighted *K'* image is employed as the continuum. The weighted factor, H₂/*K'* flux ratio, is obtained by dividing the H₂ and *K'* flux of the field stars that are believed to have no H₂ line emission. This ratio is found to be essentially the H₂/*K'* filter pass-band ratio of the OASIS camera. The uncertainty of the H₂ fluxes is 15%.

3. Results

The new images of H₂ and *K'* are presented in Figs. 1a and 1b and cover a field of $\sim 6' \times 6'$. Figure 2 shows the continuum-subtracted H₂ image, overlapped with the NH₃ contours and several marks of H₂O masers (Torrelles et al. 1992b). The nebular-like knots are labelled in the figure and listed in Table 1. Among them, the H₂ knot 1-11 previously detected (Torrelles et al. 1992a; Chen et al. 1999) is clearly seen.

H₂:7 is clearly elongated, while H₂:11 is more bow-shaped than given by Chen et al. (1999). H₂:4 and H₂:9 seem to be “melted” into a single bar while H₂:8 shows a bow-shaped wing open to the north.

In order to describe the environment of star formation in AFGL 5157, we sketch in Fig. 3 the observations previously obtained in the literature. The positions of H₂ emission (jet and shell) are also marked on it.

While the known knots could be seen more clearly and a number of new fainter ones could be observed, we have not detected H₂:12, which in fact appears fairly faint in Fig. 6b of Chen et al. (1999). This also happened in the HH 46/47 system (Micono et al. 1998), where some knots apparently changed in “shape” or vanished completely within 4 years, indicative of a rapid evolution of the individual H₂ knots.

In Fig. 2, a number of new faint H₂ knots are observed around the NH₃ core. Two new knots, H₂:13a and 13b, seem to associate with a faint continuum feature (see Fig. 1b), and to line up as a jet towards the north. At the center of the dense NH₃ core there is a new knot, H₂:14, which seems to be associated with a faint nebulous infrared object and one of the H₂O masers (Verdes-Montenegro et al. 1989; Henning et al. 1992; Torrelles et al. 1992b). To the east of H₂:3 is a small knot, H₂:3a, seeming to be separated from the H₂:3 flow. There is another jet-like knot, H₂:15, towards the east of H₂:10, and a more faint H₂ feature can be seen.

To the N–W of the NH₃ core we see seven new H₂ knots (H₂:16a–16g in Fig. 2). Among them only H₂:16a is a well-formed knot, the others are rather faint and diffuse. H₂:16a, 16c, and elongated H₂:16b seem to make up a large bow structure. These knots are likely to be lined up as a long jet-like structure with a nearly equal span between each pair of them. Furthermore, the jet seems to be traced back to H₂:14, which is very close to one of the H₂O masers and the radio continuum source (Verdes-Montenegro et al. 1989; Henning et al. 1992; Torrelles et al. 1992b). The length from H₂:16a via 16d–16g to H₂:14 is about $4'$, or $\sim 1.9 \text{ pc}$ at a distance of 1.8 kpc (Snell et al. 1988). Thus, the faint but well-collimated H₂ flow is a parsec-scaled chain flow, emanating with a roughly equal time interval from a common source embedded in the core.

Figures 1a and 2 display more clearly the shell structure of H₂ line emission around the infrared cluster (Chen et al. 1999). The western part of the shell shows a long arch ridge with diffuse emission westward. On the contrary, the eastern part of it displays two parallel ridges with a less extended diffuse structure between them, and the inner short one is newly detected.

In Fig. 1b the infrared nebula around the infrared cluster, which is clearer than that given by Chen et al. (1999), is consistent with the shell structure in Fig. 1a. But there is no trace of such an infrared nebula surrounding the dense core, which may contain a hidden cluster (see Sect. 4.3). The infrared nebula seems to only emerge from the evolved cluster.

A new knot H₂:17 is found on the southern edge of Fig. 2, slightly elongated in the NW–SE direction. Although its origin is not clear yet, it seems to be no relation to either the infrared cluster in NGC 1985 or the source(s) hidden in the NH₃ core.

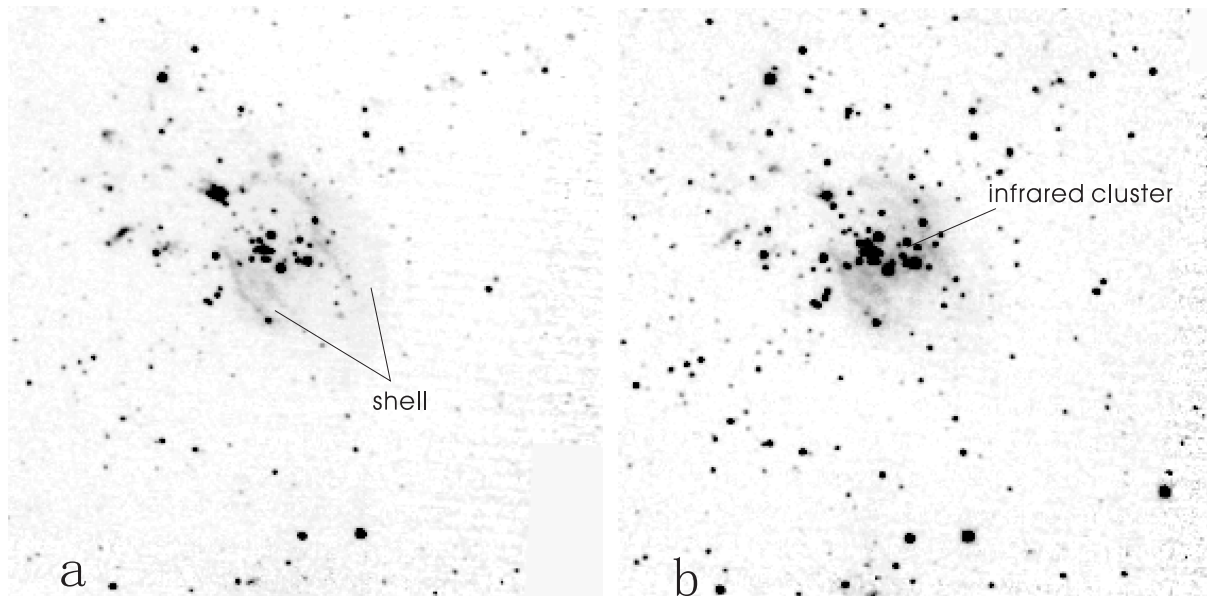


Fig. 1. a) The H₂ $v=1-0$ S(1) image of AFGL 5157 over a field of $6' \times 6'$. North is at the top and east is to the left. The shell structure around the infrared cluster is marked. **b)** The K' image of AFGL 5157 over a field of $6' \times 6'$, similar to the left panel. The infrared cluster is marked. The faint surrounding is the infrared nebula, coinciding well with the shell structure.

4. Discussion

4.1. The H₂ shell structure

The diffuse H₂ line emission is a common characteristic of the youngest infrared clusters, such as in NGC 2023, S 255, NGC 7538, S 235 (Gatley et al. 1987; Yao et al. 1997, 1999, 2000). The shell-like structures are the appearance of fluorescent H₂ emission due to the UV photon leakage by massive stars in the clusters. The spiral-like shell around the infrared cluster in AFGL 5157 strengthens the hypothesis (Chen et al. 1999) that the star-forming activity of the cluster forms the shell structure. When the sources, especially the massive ones in the infrared cluster interact with the remained material in the cloud, the diffuse line emission would be produced.

The shell structure may act as a constraint on star formation and a cluster's evolutionary status. Comparing the knots around the NH₃ core with the ridges appearing in the shell, the density of ambient molecular material seems to decrease from the core towards the cluster. In the shell, its eastern lobe, which exhibits two parallel ridges near the core, seems to be more compact and denser than the western counterpart, which shows only one ridge and more attenuation westward. This may indicate that the remaining molecular material around the cluster is denser to the east than to the west. As the density decreases from the core through the east to the west of the shell, this further confirms the conclusion previously obtained by Chen et al. (1999) that the star forming process appears to propagate from the west to the east in AFGL 5157.

4.2. The parsec-scaled outflow

The shocked H₂ knot is a good tracer of HH flows (Eisloffel & Mundt 1997), and furthermore, the chain of the knots

on a parsec scale is a better indicator of the flows. Several parsec-scaled HH objects (super-jets) are known to be associated with CO outflows (Lee et al. 2000; Gueth & Guilloteau 1999). Recently, the morphological relation between CO outflows and H₂ bow shocks has been observed in L 1448 (Bachiller et al. 1995; Dutrey et al. 1997), RNO 43 (Bence et al. 1996), L 1157 (Gueth et al. 1996), Cep E (Eisloffel et al. 1996), HH 211 (Gueth & Guilloteau 1999), and HH 212 (Zinnecker et al. 1997; Lee et al. 2000).

In AFGL 5157, the long jet flow is not as strong as those surrounding the NH₃ core and the distance from the core may imply for that the jet flow emanated prior to the latter. In Fig. 3, the newly discovered parsec-scaled H₂ flow appears along one lobe of the bipolar CO outflow straddling the core (Snell et al. 1988; Torrelles et al. 1992b), suggesting its origin in the core. This flow is likely to be powered by a massive radio continuum source, for one of the H₂O masers (Torrelles et al. 1992b) and H₂:14 knot seem to associate with it. Moreover, the point source may be a Class 0 object, similar to L 1448 (Dutrey et al. 1997) and HH 211 (Gueth & Guilloteau 1999), in which highly collimated and dynamically very young ($\sim 10^4$ yr) flows are driven by an embedded Class 0 source (Ray 2000).

There are several models proposed to link the jets with the outflows (Cabrit & Gueth 1997). One of the models, the jet-driven model, suggests that as the molecular hydrogen emission flows along the lobes of bipolar CO outflow, the latter is likely to be driven by the former (Eisloffel & Mundt 1997; Padman et al. 1997). From simulations of a jet propagating into ambient material entrained (Smith et al. 1997; Suttner et al. 1997), the CO wing emission could arise in material through jet-driven bow shocks traced by the H₂ emission. The molecular outflow is regarded to be momentum-driven by jets (Beuther et al. 2002). In AFGL 5157, the driving agent of CO

Table 1. Positions and flux measurements of Shock-Driven H₂ Features in AFGL 5157.

H ₂ Knot	α (J2000) (h m s)	δ (J2000) ($^{\circ}$ ' ")	Flux (10^{-20} W cm $^{-2}$ μ m $^{-1}$)	Aperture ^a (")	<i>FWHM</i> (")	Morphology ^b	Remark ^c
1	05 37 48.00	+32 00 09.5	20.17	12	4.7	BS	1
2	05 37 48.77	+32 00 00.1	9.98	10	4.34	E	1
3	05 37 49.98	+31 59 52.0	251.85	24	4.37	BS	1
3a	05 37 50.95	+31 59 56.1	-	-	-	K	3
4	05 37 53.31	+31 59 33.9	41.53	12	5.04	BS	1
5	05 37 45.50	+31 58 59.1	7.48	10	3.19	E	1
6	05 37 49.15	+31 59 54.6	13.04	10	4.41	K	2
7	05 37 51.72	+32 00 24.9	8.21	6	2.28	K	2
8	05 37 51.89	+31 59 26.8	34.62	16	6.06	BS	2
9	05 37 53.84	+31 59 28.4	41.56	12	5.04	K	2
10	05 37 53.80	+31 59 53.1	16.53	10	3.19	E	2
11	05 37 53.98	+32 00 18.0	25.55	16	4.59	BS	2
13a	05 37 52.39	+32 00 29.9	2.69	-	-	K	3
13b	05 37 52.53	+32 00 35.7	1.23	6	2.01	K	3
14	05 37 51.84	+32 00 03.0	1.46	6	2.49	K	3
15	05 37 54.77	+31 59 56.3	3.01	6	2.81	K	3
16a	05 37 37.79	+32 01 07.4	9.74	10	3.07	PS	3
16b	05 37 38.93	+32 00 56.3	5.40	8	5.9	PS	3
16c	05 37 39.80	+32 01 13.7	2.90	10	3.93	PS	3
16d	05 37 41.57	+32 01 44.7	3.55	10	4.54	PS	3
16e	05 37 44.51	+32 01 35.1	3.82	18	9.72	PS	3
16f	05 37 46.63	+32 01 25.3	3.15	18	5.25	PS	3
16g	05 37 49.18	+32 00 20.3	3.02	18	5.21	PS	3
17	05 37 48.24	+31 56 59.8	14.29	6	2.69	K	3

a. Apertures employed for H₂ flux measurements.

b. BS (bow-shaped); E (elongated); K (knot); PS (parsec-scaled).

c. 1. Torrelles et al. (1992a); 2. Chen et al. (1999); 3. this work.

outflow could be similarly driven by the parsec-scaled H₂ jet from the massive source hidden in the core.

There are two different timescales related to the H₂ knots and the H₂ outflow, respectively. Individual knots have de-excitation time scales of ~ 1 year and have been observed to change within a few years, like H₂:12 mentioned before. But in general the overall outflow activity lasts for at least 10^5 yr, even though it is most intense in the first few 10^4 yr. The giant flow roughly shows a periodicity in multiple outbursts. Assuming the flow velocity of 100 km s^{-1} (Bally et al. 2002; Lee et al. 2000), the time scales travelling from H₂:16g to 16f, 16f to 16e, 16e to 16d, and 16d to 16a would be $\sim 0.34 \times 10^5$ yr, $\sim 0.34 \times 10^5$ yr, $\sim 0.34 \times 10^5$ yr, and $\sim 0.48 \times 10^5$ yr, respectively. Another interval of $\sim 0.38 \times 10^5$ yr would be needed to travel from H₂:14 to 16g if H₂:14 belongs to the flow. As a whole, it is about 1.88×10^5 yr to travel from H₂:14 to H₂:16a. The dynamical timescale of a typical parsec-scaled HH object (~ 3 pc) is about 10^{4-5} yr for the velocity of 100 km s^{-1} , nearly the time-scale for both the whole accretion stage of a star and the outflow estimated from CO (Wang 2002).

4.3. The implication of an extremely embedded cluster

Besides the parsec-scaled jet (H₂:16a-g), there are 15 H₂ knots surrounding the NH₃ core. The knots should be produced by YSOs. The short dynamical time-scale of the jets suggests that

the star formation process is now taking place within the core, although we could not detect such extremely YSOs in the NIR bands.

As mentioned above, belonging to the jet, H₂:14 is associated simultaneously with both the nebular infrared source and one of the H₂O masers in the core. The massive *K*-source (nebular and linked with an H₂O maser; see Fig. 1) centered at the core would be the exciting source of the newly discovered parsec-scaled flow. Both H₂:4 and H₂:9 seem to be “melted” together as a bar, implying a strong flow happen. A few of these knots show bow-shaped patterns and seem to show bipolar flow, such as H₂:3 and H₂:11. However the majority of them, appearing non-axial-symmetrically in the core, are not all along the E-W direction of CO outflow. This illustrates that they should be most likely driven by more than one YSO. In other words, they are powered by a cluster of sources so deeply embedded that only a minority of the stars appear on our near-infrared images, hence the density of detected sources is not significantly above the detected density of field stars. We call this cluster an extremely embedded cluster to distinguish it from the neighboring infrared cluster centered at NGC 1985, which is visible in NIR bands because most of its parent material has been used up after $\sim 10^{6-7}$ yr (Chen et al. 1999).

In AFGL 5157, Torrelles et al. (1992b) have traced the HII region and some H₂O masers using VLA 3.6 cm continuum observations at the central part of the dense core (cf. the positions of the H₂O masers in Fig. 2 and the sketch of relationship

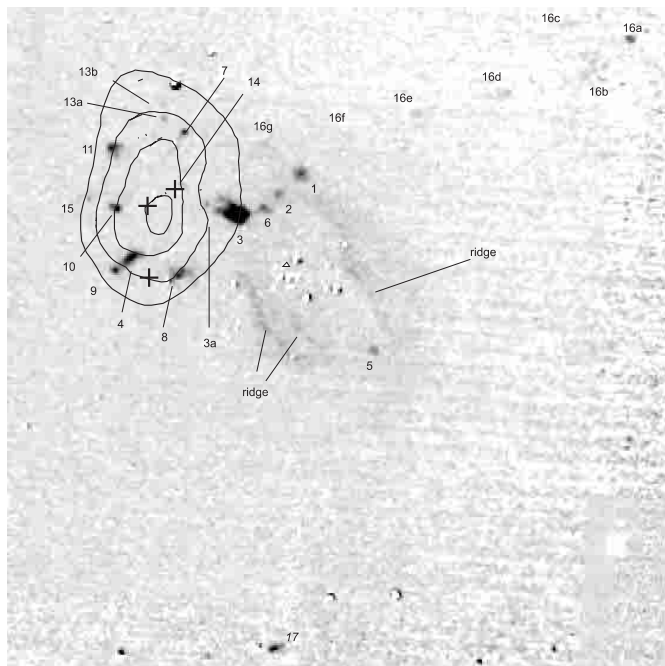


Fig. 2. The continuum-subtracted H₂ image of AFGL 5157. The H₂ knots and ridges of shell structure are marked, respectively. The superposed are the contours of the NH₃ core (Verdes-Montenegro et al. 1989; Pastor et al. 1991; Torrelles et al. 1992a), together with several plus symbols standing for the H₂O masers (Verdes-Montenegro et al. 1989; Henning et al. 1992; Torrelles et al. 1992b).

among the core, the H II region, the H₂O masers, and the CO bipolar outflow, etc., in Fig. 3). Moreover, the dense part of the core is near the knot H₂:14, implying something linking it to the latter (the jet). The existence of H₂O masers means some young massive stars were born in the core, since the H₂O masers trace the earliest evolutionary phase of massive stars (Codella et al. 1994, 1995; Palumbo et al. 1994; Codella & Felli 1995; Codella et al. 1996, 1997; Testi et al. 1997; Felli et al. 1997; Kylafis & Pavlakis 1999).

Thus, all the evidence, including the H₂ knots and jet, the radio compact H II region, the radio continuum source, and the H₂O masers in the dense NH₃ core (Verdes-Montenegro et al. 1989; Henning et al. 1992; Torrelles et al. 1992b), as well the CO outflow (Snell et al. 1988), strongly indicates the presence of a very deeply embedded cluster of very young stars, many being in their main accretion and outflow phase (Class 0 or I), and among them at least a few higher mass stars.

4.4. The H₂ line emission and evolution of clusters

There are two well-separated star formation sites in AFGL 5157: the infrared cluster and the proposed extremely embedded cluster. The latter, hidden in the dense NH₃ core, is associated with the multiple shock-driven H₂ knots/jet, while the former is obviously revealed with the diffuse H₂ shell structure emission. AFGL 5157 is a nice example of the evolutionary status of young clusters from shocked-driven to diffuse H₂ line emissions.

Due to the shocked-driven H₂ knot being highly collimated with the driving YSO, the non-axially symmetric H₂ knots should be excited by a cluster of YSOs embedded in the extremely embedded cluster (see Sect. 4.2). On the other hand, the shell is produced by the whole infrared cluster, instead of by the individual point sources in it, as described in Sect. 4.1. The mechanism of the diffuse emission differs from that of the shock-driven H₂ knot. As mentioned above, UV pumped fluorescence that occurs on the surface of molecular clouds produces such a large sheet of extended diffuse emission (Gatley et al. 1987). Hence these two types of H₂ line emissions may reflect the different evolutionary stages of the clusters.

The ambient molecular material is proposed to be denser in the core than in the infrared cluster. The extremely embedded cluster must be younger than the infrared cluster. In this scenario, the H₂ knots driven by powering sources enshrouded in the dense core should appear in the early stages of a cluster (like the extremely embedded cluster). The winds and outflows from new born stars gradually dilute the ambient material, and eventually the infrared cluster emerges as the H₂ outflow activity fades and/or disappears after several 10⁵ yr. Then the diffuse H₂ emission appears around the evolved cluster (like the infrared one). A similar scenario has been observed in other star formation regions. In AFGL 5142, three H₂ jets are linked a young cluster in its embryo stage, and in S 152, several small knots in the southern embedded cluster are associated with the dense NH₃ core (Chen 2001).

On the other hand, the diffuse emissions are always around rather evolved clusters. According to the estimation in Sect. 4.2, the H₂ knots in the jet could disappear $\sim 10^{4-5}$ yr after their formation. After $\sim 10^6$ yr (the presumptive age of the infrared cluster; Chen et al. 1999), the diffuse H₂ emission displays arc, shell, or filamentary structures as the infrared cluster interacts with the cloud remainder. A large-scaled arc structure is detected to the south of the infrared cluster in AFGL 416, two arc features are separately linked with the main cluster in S 157, and two arc features enclose the northern evolved cluster, which is further surrounded by a flower-like filamentary structure in S 152 (Chen 2001).

5. Conclusions

From the new *K'* and H₂ images of AFGL 5157, we conclude the following:

1. The parsec-scaled H₂ jet stretched out in the N-W direction of the NH₃ core runs along and drives one lobe of the bipolar CO outflow centered at the dense core. The powering source could be the massive YSO deeply embedded in the dense core.
2. The non-axially symmetric outflows are further confirmed by the newly observed H₂ knots. There should be an extremely embedded cluster embraced by the NH₃ core responsible for powering such knots/jet.
3. The multiple H₂ knots and parsec-scaled jet, together with the H II region and several H₂O masers suggest extreme YSOs (Class 0 or I) and massive point sources hidden in the extremely embedded cluster.

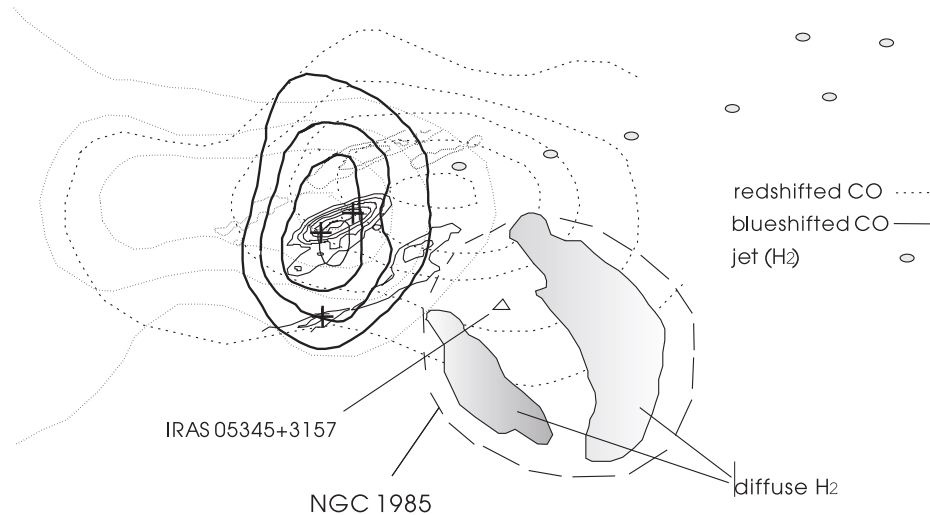


Fig. 3. The sketch of observations previously obtained in the literature and the new H₂ jet in AFGL 5157. The NH₃ core (Verdes-Montenegro et al. 1989; Pastor et al. 1991; Torrelles et al. 1992a) in thick contours is similar to that in Fig. 2, superposed with the HII region in tilted thin contours, H₂O masers in plus symbols (Verdes-Montenegro et al. 1989; Henning et al. 1992; Torrelles et al. 1992b), and CO bipolar outflow (Snell et al. 1988; Torrelles et al. 1992b). The red lobe of CO outflow is along the jet. The positions of NGC 1985 (Torrelles et al. 1992a) and IRAS 05345+3157 are also marked, coexisting with the diffuse H₂ shell (see Fig. 2 and Chen et al. 1999).

4. The H₂ shell structure around the infrared cluster is confirmed and is newly revealed with ridges. The star forming process may propagate from the infrared cluster towards the NH₃ core (the extremely embedded cluster).
5. The H₂ line emission exhibits a trend related to the evolutionary status of clusters. The highly collimated shock-driven H₂ knots could be individually associated with the YSOs of the deeply embedded cluster, while the diffuse shell structure appears around the more evolved infrared cluster.
6. The nebulae are also related to the evolutionary status of the clusters. It appears from the evolved cluster but is not observed in the extremely embedded cluster.

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