Astron. Astrophys. 331, L45–L48 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

IRAS 06562−0337, the Iron-clad Nebula: a young star embedded in a molecular cloud

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Received 15 May 1997 / Accepted 19 June 1997

Abstract. We present millimeter and sub-millimeter observations of IRAS 06562−0337, the so-called Iron-clad Nebula. It had been suggested previously that this object could be an evolved star in the transitional phase between the AGB and a planetary nebula. However, our observations show that this IRAS source lies at the center of a dense massive molecular cloud which exhibits strong lines of CO, ^{13}CO, CS, and C I. The close association of the source with this molecular cloud, the proximity to other molecular complexes, the infrared spectral energy distribution, and the main characteristics of the previously observed optical spectra, imply that IRAS 06562−0337 is a young stellar object (or a small cluster) still associated to its parent molecular cloud. IRAS 06562 is placed at 7±3 kpc from the Sun, in the anticenter direction. Its location in the Galaxy, at about 15 kpc from the galactic center, makes the object particularly interesting for studies of galactic structure.

Key words: stars: emission-line, Be – stars: formation – ISM: clouds – ISM: planetary nebulae: IRAS 06562−0337 – radio lines: ISM

1. Introduction

The identification of a nebulous object as a Planetary Nebula (PN) or a Young Stellar Object (YSO) is not always straightforward. In some cases, a nebulous object is classified as a PN on the basis of its morphological appearance or some features of its optical spectrum. This can lead to confusing situations, as confirmed by the relatively large lists of "misclassified planetary nebulae" already published (e.g. the 350 objects listed by Acker et al. 1992). Fortunately, for some objects, observations of molecular lines in the millimeter range can help in elucidating their actual nature. As some examples, He 2-77 (298−0.1), K 4-45 (96+1.1), and M 1-78 (93+1.1), which were first believed to be compact PNe, and have entries in the PK catalogue, have been recently recognized to be compact H II regions associated with massive molecular clouds (Huggins et al. 1996, and references therein).

In this paper we deal with the classification of IRAS 06562−0337 (hereafter referred to as IRAS 06562). This object is particularly interesting because it was believed to be a proto-PN (PPN) or one of the youngest known PNe. The PPNe and young PNe are very rare because the transition time from the AGB phase to the PN stage is known to be very short, of the order of 10^3 yr (e.g. Kwok 1993). So the identification of a new of these rapidly-evolving objects is always of interest.

IRAS 06562 was first classified as a possible PN by MacConnell (1978) from an Hα objective-prism survey, but it appeared in the list of Hα emission stars of Acker et al. (1987) with the comment "not a PN". Nevertheless, the IRAS flux densities, completed with near-IR photometry from the ground, led Iyengar (1987) and Manchado et al. (1989) to note that the object is similar to young dusty PN. Optical spectroscopy obtained in 1990 by García-Lario et al. (1993) (hereafter referred to as GMSP) revealed the emergence of forbidden emission lines of [O III], [N II], and [S III] —not detected in previous spectra taken in 1987 and 1988— accompanying a dramatic increase in the He I intensity. This was the main argument to suggest that IRAS 06562 was a PN in the making. In fact, it seems natural to interpret the ionization of the low density gas in the nebula as a consequence of the temperature increase of the central star (as models predict for proto-PNe). However, the forbidden line emission disappeared in 1992, and GMSP cautioned that although the most natural explanation of the observations was that IRAS 06562 is a PPN, "some other alternatives may not be completely ruled out".

In a recent *Letter*, Kerber et al. (1996) have reported that the high-excitation forbidden lines were not observed in high-sensitivity spectra taken in April 1996. These spectra showed however a multitude of permitted and forbidden Fe II lines, which led Kerber et al. to call IRAS 06562 "the Iron-clad" Nebula. In fact, if the object were a PPN or a young PN, the disappearance of the [O III], [N II], and [S III] lines, together with the Fe II-rich spectrum would make it really extraordinary. Thus a more detailed study on its nature was needed. The mm and sub-mm observations presented in this *Letter*, together with a detailed summary of all the known properties of the source, imply that, rather of being an extraordinary PPN or young PN, IRAS 06562 is a young stellar object still associated with the massive molecular cloud in which it was born.

2. Observations and Results

Observations at mm wavelengths were carried out with the IRAM 30-m telescope in 1993 August and 1997 May. We used three SIS receivers operating near λ 1.3, 2.0, and 2.6 mm to simultaneously observe the lines of CO (2→1), CS (3→2) and CO (1→0). Spectra of the ^{13}CO (1→0 and 2→1) and CS (2→1) lines were also obtained at several

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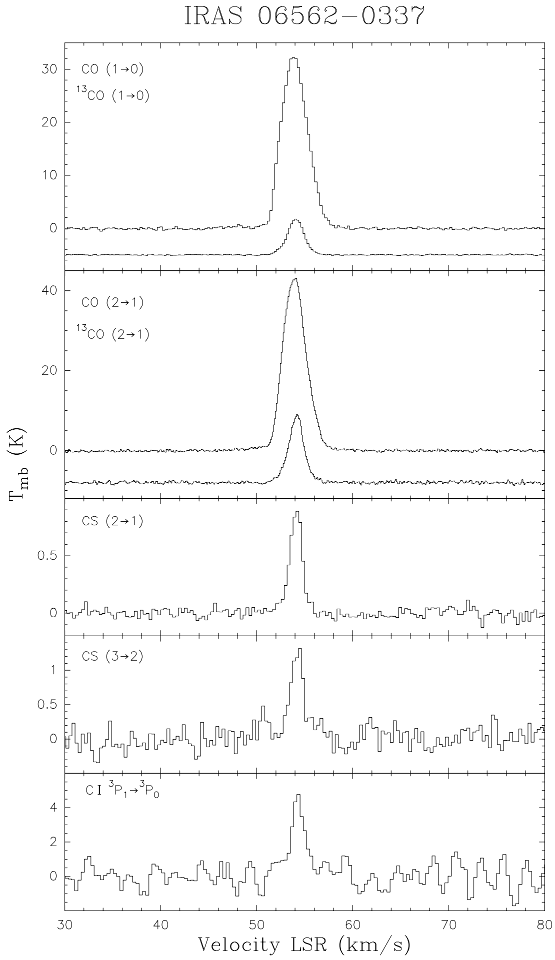

Fig. 1. CO and ^{13}CO (1⟶0 and 2⟶1), CS (2⟶1 and 3⟶2), and C I ($^3P_1$⟶$^3P_0$) spectra observed toward the central position of IRAS 06562−0337 (α=6:56:15.2, δ=−3:37:00 (1950.0)).

positions. The telescope beam size and efficiency are 12″ and 0.45 at 230 GHz, 18″ and 0.55 at 147 GHz, and 24″ and 0.60 at 115 GHz. The spectrometers used were autocorrelators, giving a velocity resolution of 0.10, 0.32 and 0.26 km s^{-1}, respectively. The pointing of the telescope was regularly monitored by observing standard continuum sources, and was found to be accurate to within 3″.

The C I $^3P_1$⟶$^3P_0$ line at 492 GHz (λ 609 μm) was observed with the CSO 10.4 m telescope on Mauna Kea in 1993 March. We used a SIS receiver with DSB noise temperature of ∼200 K. The observations were made in good weather, with a typical system temperature above the atmosphere and corrected for attenuation losses of 2000 K. We used a 500 MHz accousto-optical spectrometer with an effective resolution of 0.6 km s^{-1}. The telescope beam size at 492 GHz is 15″, and the main beam efficiency for the observations was 41% as measured by CSO. The telescope pointing was found to be accurate to within 4″.

For all observations, the intensity calibration was carried out using the chopper wheel technique, and the line intensities are reported here as main beam brightness temperatures. Figure 1 shows the CO, CS, and C I spectra observed toward the nominal IRAS position. Figure 2 shows the maps in the 1⟶0 and 2⟶1 lines of CO and in the 3⟶2 line of CS. The points in the bottom panel mark the observed positions. Weak (∼1 K) CO emission at LSR velocities close to that of the central region was also detected toward some selected positions at distances up to 5′ from the IRAS source.

3. Properties of the Nebula

3.1. Location in the Galaxy

IRAS 05662 lies close to the galactic plane in the anticenter direction ($l^{\rm II}$=217.0, $b^{\rm II}$=−0.05). The LSR velocity of the molecular emission is 54.0±0.2 km s^{-1} (see Fig. 1), in good agreement with the LSR velocity of the optical lines (50±6 km s^{-1}, GMSP). Large-scale surveys of the galactic plane in H I show that there is a massive interstellar cloud in this region and in the same range of velocities (Burton & te Lintel Hekkert 1985). Moreover, in a radius of about 30′ around IRAS 06562, there are at least three "radio-quiet" H II regions cataloged by Blitz et al. (1982): BFS 56, 57, and 58. The LSR velocity of BFS 56 and 57 is about 26 km s^{-1}, so they are probably not physically related to IRAS 06562. However, BFS 58, which lies at 30′ from IRAS 06562, has a velocity of 50 km s^{-1} (as measured by Blitz et al. 1982 in CO), and it could be connected to IRAS 06562.

The distance to IRAS 06562 determined from a standard galactic rotation curve (Burton 1974) is 7±3 kpc (for a distance to the galactic center of 8.5 kpc). It is therefore at a large galactocentric distance (∼15 kpc) which makes it particularly interesting for studies of the galactic structure and evolution.

3.2. CO emission

IRAS 06562 presents bright CO and ^{13}CO emission. The CO 2⟶1 line intensity reaches 44 K at the peak, strong (>5 K) emission extends over a region of ∼1′ radius, and weak (0.5 K) emission is still seen 5′ south of the source. The emission is peaked on the IRAS source, indicating that the cloud is centrally condensed and/or heated by the star. We can obtain a lower limit to the mass of the cloud by assuming that the *average* volume density is $\gtrsim$500 cm^{-3} in the region where the lines are strong (>5 K for CO and >1 K for ^{13}CO), i.e., in a sphere of about 1′ radius. This way, we obtain a cloud mass M>1000 M$_\odot$. We stress that this limit is much higher than the limit of 7 M$_\odot$ obtained by GMSP. Our mass estimate is based in a new estimate of the distance, a complete map, and takes into account the large CO opacities indicated by the strong ^{13}CO emission. In fact, the whole cloud could be much more massive than 1000 M$_\odot$, since the weak emission detected at large distances from the peak indicates the presence of an extended "halo" (5′ is equivalent to 10 pc at the distance of IRAS 06562). Moreover, the density of the innermost region is much higher than the value assumed here (see next Subsection).

Weak wings are observed in the central CO spectra indicating that the source is exciting an outflow of ∼2–3 km s^{-1}. The outflow seems bipolar with the blue and redshifted emissions placed North-South. However, the outflow is weak and compact ($\lesssim$20″), so the resolution of our observations is not enough to study its structure. Bipolar outflows are ubiquitous around YSOs (Bachiller 1996). On the other hand, typical CO intensities in PNe are $\lesssim$2 K (e.g. Huggins et al. 1996), i.e. much smaller than that observed around IRAS 06562.

In summary, all the features seen in the CO data are characteristics of a star-forming region.

3.3. CS emission

The CS 2⟶1 and 3⟶2 emission is relatively strong (∼1 K) and well peaked around the IRAS source. (Note that the CS lines are not de-

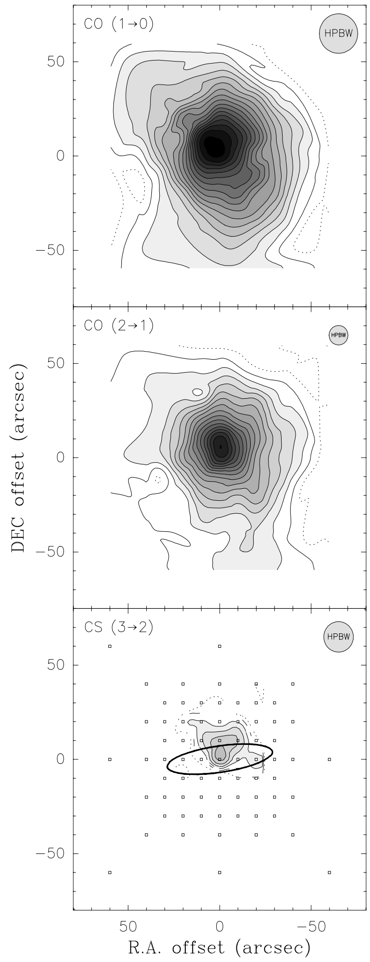

Fig. 2. CO (1⟶0 and 2⟶1) and CS (3⟶2) maps of the molecular cloud around IRAS 06562−0337. Fist contour and step are 6 K km s^{-1} for CO 1⟶0, 10 K km s^{-1} for CO 2⟶1, and 0.5 K km s^{-1} for CS. The nominal IRAS position of the source is indicated by its positional error ellipse in the CS map.

tected in PNe, since the fragile CS molecules are rapidly destroyed at the proto-PN stage, Bachiller et al. 1997). The 3⟶2 emission is concentrated in a region of about 20$''$ (0.7 pc) around IRAS 06562. The 3⟶2/2⟶1 line intensity ratio provides an estimate of the gas volume density. By diluting the 3⟶2 map to the resolution of the 2⟶1 observation, and using a Large Velocity Gradient (LVG) code, we estimate that the average density in the central 20$''$ region is ∼3 10^5 cm^{-3}. Thus, the mass contained in this region, by assuming spherical symmetry, is ∼3400 M$_\odot$, although the mass of the whole cloud could be much higher, as indicated in the previous Subsection.

3.4. *C I emission*

Strong C I $^3P_1$⟶$^3P_0$ emission (∼5 K) has been detected in a single spectrum observed toward IRAS 06562. The C I peak velocity and the linewidth are in good agreement with those of the CO lines (see Fig. 1), indicating that the neutral atomic region is closely associated with the molecular cloud.

The C I line provides a direct estimate of the beam-averaged column density of C I atoms in the cloud. For optically thin conditions, assuming a kinetic temperature of 50 K, and under standard assumptions (e.g. Phillips & Huggins 1981), we estimate a C I column density of 1.4 10^{17} cm^{-2}. Thus, the C I/CO column density ratio is found to be <0.3 (this is a lower limit due to the high CO opacity). Such a value is significantly lower than the ratio found in evolved PNe. For instance, the C I/CO ratio has been measured to be 6–10 in the Ring (Bachiller et al. 1994) and in the Helix Nebula (Young et al. 1997). Although this ratio could be lower in PPNe, the value of the C I/CO ratio in IRAS 06562 is entirely consistent with the typical values found in interstellar molecular clouds (Phillips & Huggins 1981)

3.5. *CO, CS, and C I linewidths*

The widths of the mm and sub-mm lines are in the range from 1.5 to 3.5 km s^{-1}, quite unlike those of usual PPNe and young PNe. For orientation, we recall that the CO linewidths in IRC+10216, CRL 2688, CRL 618, and NGC 7027, four objects sampling the evolution from the AGB to the young PN phases are 25 km s^{-1} in IRC+10216 and >40 km s^{-1} in the other three objects (Bachiller et al. 1997). However, a linewidth of ∼2 km s^{-1} is not unexpected for an interstellar molecular cloud of moderate mass.

3.6. *Spectral energy distribution (SED) and luminosity*

The SED of IRAS 06562 is shown in GMSP (their Fig. 2). The spectrum rises from the visible to the far-IR. The total luminosity of the source, before correction for extinction, obtained by integrating the observed flux from the visible to the far IR and extrapolating longwards of 100 μm is ∼430D^2 L$_\odot$, where D is the distance in kpc (see GMSP). This results in a luminosity of 2 10^4 L$_\odot$ at the assumed distance of 7 kpc. The actual luminosity could be at most a factor of 2 higher after correction for extinction, taking into account the value of $E(B-V)$=1.75±0.25 derived from the analysis of the optical spectra by GSMP. The flux densities place IRAS 06562 just at the border of PNe and H II regions in the IRAS color-color diagrams of Jourdain de Muizon et al. (1990) and García-Lario et al. (1997). Very few PPNe or PNe are known to be sufficiently cold and dusty to present this kind of spectrum (see for instance CRL 618, Martín-Pintado et al. 1988; and NGC 6781, Bachiller et al. 1993). On the other hand, the SED of IRAS 06562 is similar to that of embedded YSOs. In particular, its SED is comparable to those of Class I low-mass YSOs (Ladd et al. 1991) and to those of Group II Herbig AeBe stars (Hillenbrand et al. 1992), i.e. young stars or star/disk systems which are surrounded by their remnant star-forming clouds.

3.7. *Optical spectra*

As described in the Introduction, the optical spectrum has been the main argument for identifying IRAS 06562 as a newly forming PN, especially the detection of forbidden lines of high excitation class. However, these lines disappeared in 1992, and have not been detected again (GMSP, Kerber et al. 1996).

Certainly, some features in the spectrum of IRAS 06562 are also observed in post-AGB stars, but such features are even more characteristics of YSOs of intermediate to high mass. First, in these YSOs the mass-loss phenomena are known to be extremely important, and short-term variability is common, since the mass-loss is known to happen in an episodic manner. P Cyg profiles, as observed in the Hα line toward IRAS 06562 by GMSP, are indeed relatively common in young objects. In particular, P Cyg profiles are seen in 20% of the Herbig AeBe stars (Finkenzeller & Mundt 1984). Finally, with respect to the multitude of permitted and forbidden Fe II lines, it has to be noted that these are indicative of the presence of a dense ($>10^7$ cm^{-3}) circumstellar core. Although these lines could have been detected in a few PPNe or young PNe (see discussion by Kerber et al. 1996), the most common class of objects presenting these lines are the young Be stars (Allen & Swings 1976). This class is represented by XX Oph, the so-called Merrill's Iron Star (Merrill 1951), and η Car, a Luminous Blue Variable (LBV) of about 100 $M_\odot$. [Fe II] lines are also common in the spectra of Herbig AeBe stars (see some examples in Finkenzeller 1985).

4. Summary and Conclusions

Taking together the wealth of observations described above, we are led to conclude that IRAS 06562 is a young star still closely associated with the parent cloud in which it was born. Similar IRAS sources, also beyond the solar circle, have been studied by Wouterloot & Brand (1996, and references therein) and are also recognized as star-forming regions.

The variability of the optical forbidden lines in IRAS 06562 is well understood as a result of episodic mass loss phenomena. In fact, a CO outflow seems to be driven from the star. IRAS 06562 is not associated with large amounts of ionized gas (the flux density at λ 6 cm is <0.1 mJy, GMSP), indicating that it is similar to the radio-quiet H II regions BFS 56–58 (Blitz et al. 1982) which lie in its neighborhood. This, and the richness in Fe II lines of the optical spectrum, points to a young intermediate-mass B star. A single ZAMS B0–B2 star could account for the estimated luminosity of 2 10^4 $L_\odot$.

IRAS 06562 fulfills all the criteria which define the Herbig AeBe stars as a class (see e.g. Thé et al. 1994). Namely: (i) spectral type A or earlier with emission lines in the spectrum, (ii) the star lies in a obscured region, and (iii) the star illuminates a nebulosity in the vicinity (GMSP). This, and the characteristics of the molecular cloud around the star, point to a Be star of Group II in the sense of Hillenbrand et al. (1992), i.e. a young Be star which remains within the placental dense cloud in which it was formed. However, there are other alternatives deserving further investigation. First, the optical emission line spectrum could arise from an extended H II region similar to the other nearby radio quiet regions. Second, we could be looking to a small cluster of young stellar objects.

The sporadic presence of the [O III] lines is surprising. The most plausible explanation is that the episodic [O III] lines are due to a particularly violent mass-loss event in IRAS 06562 itself or to any unseen low-mass companion which could drive a HH jet. In fact, [O III] is seen in high excitation HH objects (such as HH 1–2 and HH 111), we know that there is a bipolar CO flow around IRAS 06562 (see *3.2*), and such outflows are thought to be driven by eruptive ionized jets (Bachiller 1996).

The observations reported here underscore the risks of a quick classification of an object as a PN. It appears that the firm classification of a PPN or a young PN in some particularly difficult cases as the one discussed here has to be done on the basis of multiwavelength observations.

Acknowledgements. We are grateful to Drs. P.J. Huggins, M. Tafalla, and F. Palla for enlightening discussions. An anonymous referee is acknowledged for helpful suggestions. CSO is operated by the California Institute of Technology under funding from the NSF. RB and MPG acknowledge support from Spanish DGICYT grant PB93–048, and PGL from PB94–1274.

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