The evolutionary status of The Frosty Leo Nebula

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Abstract. We present new observational data for IRAS 09371+1212, the Frosty Leo Nebula, in the form of infrared spectra from 2.2–2.5\textmu m which reveal photospheric bands of CO. The $^{12}$CO/$^{13}$CO band ratio determined is similar to those exhibited by evolved K giant stars, and supports the proposal that the object is highly evolved. The equivalent width of the CO bands implies, however, that the spectral type lies in the range G5III to K0III, somewhat earlier than K7III, as derived from colours and optical spectra. The smaller equivalent widths of the CO bands may reflect a low metal abundance which could fit well with the considerable height of the source above the galactic plane (>0.9kpc).

1. Introduction

The Frosty Leo Nebula, IRAS 09371+1212, remains unique with its extremely deep 3.1\textmu m absorption feature, almost two decades in depth, its twin far-infrared emission features at 44 and 62\textmu m, and its abnormal location, >0.9kpc from the plane of the Galaxy. Forveille et al. (1987; hereafter FMOL) concluded, primarily on the basis of its 2.6mm CO emission spectrum, that it is a post-AGB star with a bipolar circumstellar envelope, and suggested water ice mantles around the grains as the source of the excess emission in the 60\textmu m IRAS band.

As noted by FMOL and Robinson, Smith & Hyland (1992; hereafter RSH) the object appears to have evolved rapidly as its luminosity \[250(d/kpc)^2L_\odot\] has apparently decreased by about an order of magnitude since the circumstellar envelope was ejected, and the lack of significant amounts of warm dust indicates that dust is not currently forming near the central source. RSH suggested the object could possibly be a weak-line T Tauri star in the final stages of ejecting its embryonic dust shell.

A seminal observational test, suggested by RSH, to determine the evolutionary status of IRAS 09371+1212, is to determine the $^{12}$C/$^{13}$C ratio from the first overtone photospheric bands of CO which should be present at around 2.3\textmu m in a late type source. In highly evolved objects this ratio lies in the range of \(~5–20\) (e.g., Lambert & Ries 1981), while in pre-main-sequence objects and local molecular clouds the ratio is \(>60\) (Langer & Penzias 1993) and closer to the solar value \(~90\).

Here we report spectroscopic measurements of the first overtone bands of $^{12}$CO and $^{13}$CO at \~2.3\textmu m of IRAS 09371+1212 which have been used to deter-
2. Bourke, Hyland, Robinson, & Luhman

Figure 1. IRIS spectrum of IRAS 09371+1212 (resolution ~450). The first overtone photospheric bands of $^{12}\text{CO}$ are clearly visible, and the $v = 2 - 0$ bandhead of $^{13}\text{CO}$ at 2.35 $\mu$m is also evident.

mine the $^{12}\text{C}/^{13}\text{C}$ isotope ratio, and so provide clear confirmation of its evolved status. The observations were obtained with IRIS on the AAT (16 Feb. 1992; Fig. 1), and Fspec on the Steward 2.3m Bok Reflector (19 Nov. 1996; Fig. 2).

2. Results and Discussion

2.1. The $^{12}\text{CO}/^{13}\text{CO}$ band strengths and the evolutionary status

The abundance ratio $^{12}\text{C}/^{13}\text{C}$ derived from the 2.3$\mu$m spectrum (Fig. 1) is ~10 (e.g., Frogel 1971). This result establishes that IRAS 09371+1212 is an evolved object (which is likely to be on or beyond the AGB). In support of this argument, Barnbaum, Morris & Forveille (1996), from observations of $^{12}\text{CO}$ and $^{13}\text{CO}$ $J=1-0$ near 2.6mm, have determined that $^{12}\text{C}/^{13}\text{C}$ may be as low as 2.

2.2. The spectral type

The best estimate of the spectral type, based on optical spectra, is K7II to III, with a distance of 1.0-4.3 kpc (Mauro, Le Brogne & Picquette 1989). In Figure 2 we show a high resolution spectrum of IRAS 09371+1212, along with spectra of giants from Kleinmann & Hall (1986) and a composite FU Orionis spectrum. From this figure we see that both the $^{12}\text{CO}$ and $^{13}\text{CO}$ ($v=2-0$) bandheads match well with those of the K0III standard, and the strength of the photospheric CO bands are weaker than that expected for a K7 giant. The equivalent width of the CO lines is found from Figure 1 to be ~53Å which implies a J–L intrinsic colour of ~0.6 (Hyland 1974), and a spectral type of G5 to G8, or K0 at the latest (Frogel 1971; Bessell & Brett 1988).

Qualitatively the spectrum of IRAS 09371+1212 matches the spectrum of a K0III star far better than that of a K5III or later star, although none of the spectra presented in Figure 2 match the spectrum of IRAS 09371+1212 per-
The evolutionary status of Frosty Leo

Figure 2. Fspspec spectrum of IRAS 09371+1212 (heavy line), with a resolution of ∼1200, compared with standard spectra and a composite FU Orionis spectrum.

fectly. In order to match the 2.2–2.5µm spectrum of IRAS 09371+1212 with the later spectral types requires that IRAS 09371+1212 also contains a featureless continuum, thereby diluting the observed bands. However, the spherical circumstellar dust model of RSH implies that the maximum grain temperature is ∼70K, too low to give rise to sufficient emission in the near infrared to reduce the observed strengths of these bands. The object therefore appears anomalous in regard to its spectral type.

As seen in Figure 2, the 2µm spectrum of IRAS 09371+1212 is also well matched by the composite FU Orionis spectrum. However, shortward of 2.2µm FU Ori stars show strong absorption due to photospheric water (e.g., Mould et al. 1978), which is not seen in the full K-band spectrum of IRAS 09371+1212 and effectively rules out IRAS 09371+1212 being an FU Ori object.

2.3. Consequences of the evolutionary status and the low luminosity

The evolved nature of IRAS 0937+1212 raises a number of issues which need to be resolved. At this stage of evolution the source should have undergone a helium flash. However the luminosity is only 250(d/kpc)^2L☉, and appears to be too low for a helium flash to have occurred (Lattanzio 1986). Furthermore, if the two stars in the system have approximately equal magnitudes at both J and H (Roddier et al. 1995), then they each have a luminosity of only 125 L☉. This demands that either (i) the luminosity was much larger in the past, and has
somehow decreased dramatically, or (ii) the object is much further away than current estimates.

Each of these alternatives raises further interesting issues. Although solar mass stars undergo significant luminosity changes during the helium flash phase (Vassiliadis & Wood 1993), theoretically these are only of the order of a factor of three, and it would appear most unlikely that the luminosity could decrease to the level of 125–250$L_\odot$ from the typical helium flash luminosity required for a G8–K0 star undergoing thermal pulses of $\sim 1500L_\odot$. Yet, at the extreme end of the models of Vassiliadis & Wood it can be seen that a one solar mass star undergoing a helium flash can exhibit a drop of a factor of seven in luminosity over a very short time scale, on the order of 50–100 years. It is therefore possible that IRAS 09371+1212 is in such a very shortlived phase of evolution.

Nevertheless, the lowest luminosity attained $\sim 700L_\odot$ would require that the source with its high galactic latitude of $b=42.7^\circ$ would be at a distance of 2.4 kpc, and be 1.6 kpc above the galactic plane (assuming L* $\sim 125L_\odot$). Such a height might suggest that the star is either an outer disk object or has halo characteristics. In either case one would expect that the source might exhibit a lower than solar metal abundance. We note that the measured strength of the CO bands is considerably weaker than would be expected for a K7 star. This may be an indication of a lower CO abundance related to an overall metal weakness for the object, which would be consistent with the above views.

Alternatively, assuming the luminosity of IRAS 09371+1212 is similar to normal planetary nebula central stars ($\sim 3000L_\odot$), its distance would then be 3.5kpc, and the height above the plane 2.3kpc, which is not improbable (Phillips & Cuesta 1997). It may simply be that IRAS 09371+1212 is such an object.

**References**

Barnbaum, C., Morris, M., & Forveille, T. 1996, BAAS, 189, number 97.15
Bessell, M.S., & Brett, J.M. 1988, PASP, 100, 1134
Forveille, T., Morris, M., Omont, A., & Likkel, L. 1987, A&A, 176, L13 (FMOL)
Frogel, J.A. 1971, PhD thesis, California Institute of Technology
Hyland, A.R. 1974, in Highlights of Astronomy, Vol 3, ed. G. Contopoulos (Dordrecht: Reidel) 307
Kleinmann, S.G., & Hall, D.N.B. 1986, ApJS, 62, 501
Lambert, D.L., & Ries, L.M., 1981, ApJ, 248, 228
Langer, W.D., & Penzias, A.A. 1993, ApJ, 409, 539L
Lattanzio, J.C. 1986, ApJ, 311, 708
Mauron, N., Le Borgne, J.-F., & Picquette, M. 1989, A&A, 218, 213
Mould, J.R., Hall, D.N.B., Ridgway, S.T., Hintzen, P., & Aaronson, M. 1978, ApJ, 222, L123
Phillips, J.P., & Cuesta, L. 1997, A&A, 326, 831
Robinson, G., Smith, R.G., & Hyland, A.R. 1992, MNRAS, 256, 437 (RSH)
Roddier, F., Roddier, C., Graves, J.E., & Northcott, M.J. 1995, ApJ, 443, 249
Vassiliadis, E., & Wood, P.R. 1993 ApJ 413 641