Infrared Classification of Young Stellar Objects

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Abstract. The radiative transfer equation for a dusty envelope as close as possible to an embedded central source possesses scaling properties. For a given dust chemical composition, the solution depends only on overall optical depth and the functional form of the radial dust distribution. All other physical parameters (luminosity, overall density, etc.) do not affect the solution independently, only through their effect on the overall optical depth.

We model infrared emission for dust density distributions ranging from a stationary outflow ($1/r^2$) to a constant density, and dust grains composed of astronomical silicate and amorphous carbon. Preliminary results demonstrate that IRAS color–color diagrams can be parametrized in terms of scaling analysis. We find that the dust in envelopes around young stars resembles a $1/r$ distribution with the 100 μm optical depth ranging from 0.001 to 1. The evolution of these objects from the proposed class 0 to class III appears to reflect a decrease in overall optical depth.

1 INTRODUCTION

Infrared spectra of young stellar objects (YSO) form distinct groups. This observation initiated several proposals for detailed classification schemes. The most widespread classification involves α, the slope of the log-log plot of the spectral energy distribution between a near-infrared and an IRAS wavelength (Adams et al. 1987). YSOs are classified as protostars if $\alpha < 0$ (class I), pre-main-sequence stars for $0 \leq \alpha < 2$ (class II) and reddened main-sequence stars when $\alpha > 2$ (class III). Recently, a new class (class 0) was proposed for sources presumed to be even younger than protostars and surrounded by significantly larger amounts of circumstellar material (André et al. 1993). All other classification schemes were shown by Myers & Ladd (1993) to be mutually equivalent.

The separation of all Galactic infrared spectra into distinct classes can be seen directly in the IRAS color-color diagrams. The IRAS Point Source Catalogue lists 5687 objects with good quality fluxes in all four bands (12 μm, 25 μm, 60 μm and 100 μm). However, most listed fluxes are still contaminated by background cirrus emission at 100 μm, and to a lesser extent also at 60 μm (Ivezić & Elitzur, 1995; hereafter IE). The 821 uncontaminated sources are plotted in Figure 1. *These are the only Galactic point sources with reliable fluxes in all four wavelength bands.* The source distribution in the IRAS color-color diagrams displays a clear structure rather than random scatter. Note that IRAS colors for all black bodies with temperature $\gtrsim$ 2000 K are the same (Rayleigh-Jeans point). Distinct spectral classes are also reflected in various phenomenological associations of objects, delineated as boxes. It is obvious that infrared spectra of young and late-type stars are very different. Indeed, both associations and their differences are expected from general scaling properties of the radiative transfer problem.

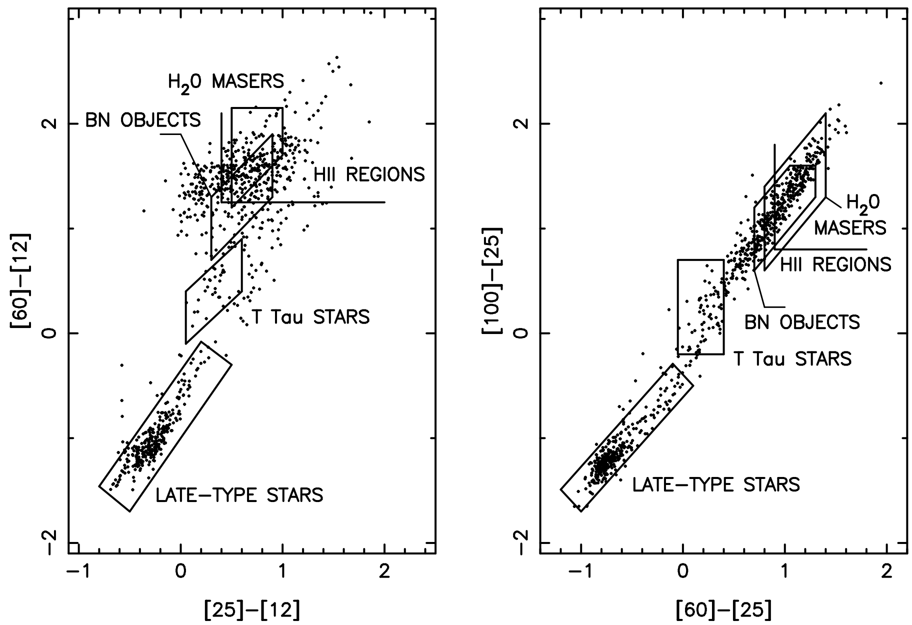

Fig. 1. Color-color diagrams of all IRAS sources, displayed as dots, with good quality fluxes at all four wavelength bands and uncontaminated by cirrus emission. Boxes delineate phenomenological associations: late-type stars (van der Veen & Habing, 1988), T Tau stars (Harris, Clegg & Hughes, 1989), Becklin-Neugebauer (BN) objects (Henning, Pfau & Altenhoff, 1990), HII regions (Wood & Churchwell, 1989) and H_2O masers detected in YSOs (Wouterloot & Walmsley, 1986). *1a* [60]-[12] vs. [25]-[12] diagram. *1b* [100]-[25] vs. [60]-[25] diagram.

2 Scaling Properties of the Radiative Transfer Problem

How do different spectral classes form and why are YSOs so different from late-type stars? We have shown (IE) that the radiative transfer problem in an isotropic medium surrounding a central source of radiation posses general scaling properties. When the dust is as close as possible to the central source, the solution of the radiative transfer equation is fully determined by two quantities: the normalized density profile $\eta = n(r)/\int n(r)dr$ and the overall optical depth τ at some fiducial wavelength. The radiative characteristics of the central source are largely irrelevant for the spectral properties of the emergent IR radiation. As a result, for a given dust chemical composition, each density profile

η produces a family of solutions corresponding to a track in the color-color diagrams. All tracks start from the common origin, the Rayleigh-Jeans point, and position along the track is uniquely determined by τ. Other physical parameters (luminosity, overall density, size of the system etc.) do not affect the solution independently, only through their effect on the overall optical depth. Dust chemical composition does not vary significantly among infrared objects and overall optical depths span about the same range. Therefore, *young and late-type stars have such uniquely different infrared spectra because the functional forms of their dust density distributions are different.*

3 Results and Discussion

As a first approximation we have calculated emerging spectra for distributions described by power-laws[1] r^{-p}. The dust grains are composed of amorphous carbon and astronomical silicate with evaporation temperature of 800 K. Optical depths at 100 μm vary from 0 to 10. The central object is taken as a black body of 4000 K since the actual temperature is irrelevant at IRAS wavelengths as long as it is $\gtrsim$ 2000 K. The emerging spectra are convolved with the IRAS instrumental band profiles to produce the appropriate fluxes for the evaluation of IRAS colors. Preliminary color-color tracks are presented in figure 2 which shows that the model tracks properly delineate the region populated by IRAS sources. For a given dust composition, different families of objects can be associated with different p and τ. For example, late-type stars are only found in the region corresponding to $p \sim 2$ (we have verified this association from detailed modeling; IE). YSOs are distributed in the regions corresponding to $\frac{1}{2} \leq p \leq \frac{3}{2}$, in agreement with detailed modeling of some individual sources (e.g. Barsony & Chandler, 1993). Since position in a color-color diagram depends also on grain composition, the value of p for a particular source can not be uniquely determined without additional spectral data to provide information about the chemical composition (e.g. IRAS LRS spectra). However, most YSOs appear to congregate around the tracks for $p \sim 1$ irrespective of chemical composition. If correct, this result would provide a strong constraint on current theories of proto-stellar collapse. In free-fall one expects $p = \frac{3}{2}$ (Shu, Adams & Lizano, 1987), but this can change by effects of magnetic fields, outflows, rotation etc. For example, models for collapsing clouds with ambipolar diffusion produce $p \sim 0.9$ (Lizano & Shu, 1989).

The evolution of YSOs from class 0 to class III seems to correspond to an overall decrease in optical depth irrespective of the grains chemical composition or the precise value of p. Deeply embedded sources enter a diagram from the upper right corner and move toward the lower left as τ decreases, i.e. as their envelope mass decreases. It is noteworthy that IRAS 16293-2442, the best candidate so far for a protostellar collapse, is the reddest source in the diagrams.

[1] Similar calculations were performed for BN objects by Gürtler et al. (1991). Here we consider all IRAS sources.

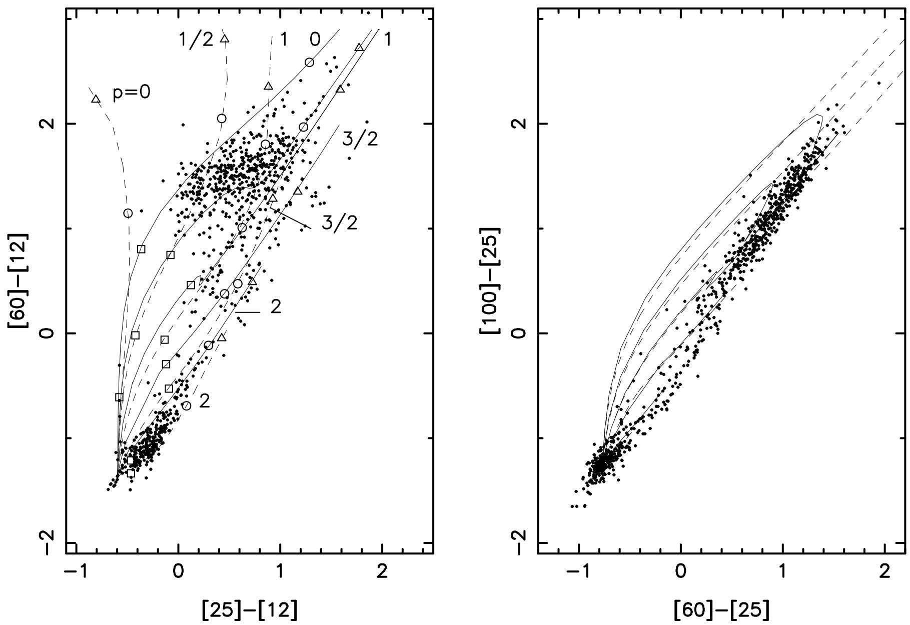

Fig. 2. IRAS color-color diagrams same as figure 1. Lines are preliminary model results for dust density distributions described by power-laws r^{-p} with $p = 0, \frac{1}{2}, 1, \frac{3}{2}$ and 2 (as marked) and grains composed of amorphous carbon (solid lines) and astronomical silicate (dashed lines). The common origin of all tracks is the Rayleigh-Jeans point. Distance from that common origin along each track increases with optical depth. Symbols indicate $\tau(100\mu\text{m}) = 0.001$ (squares), 0.1 (circles) and 0.3 (crosses).

After all of the surrounding dust is cleared, a YSO finishes its journey through the infrared color-color diagrams as a naked star at the Rayleigh-Jeans point.

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