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THE *IRAS* COLORS OF NORMAL GALAXIES

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ABSTRACT

In the *IRAS* color-color diagram, galaxies powered only by star formation are distributed in a band such that as systems get cooler at 12/25 μm they get warmer at 60/100 μm. A simple phenomenology is proposed which describes the emission from each galaxy as a combination of two components: cool, relatively constant "cirrus" emission from the neutral medium, and from "active" regions warmer emission whose colors depend on mean physical parameters in these regions. The model accounts for the *IRAS* colors of all galaxies detected as point sources in all four bands. The model implies that a galaxy's far-infrared flux as measured by *IRAS* is *not* simply proportional to the recent star formation rate, because only a (variable) fraction of the infrared is due to massive young stars, and only part of these stars' luminosity is reemitted in the infrared.

Subject headings: galaxies: photometry — infrared: spectra

I. INTRODUCTION

Except for galaxies dominated by a quasar-like nucleus, emission from galaxies into the *IRAS* photometric bands is mostly due to thermal radiation from interstellar dust grains heated by starlight. In what follows, systems satisfying this assumption will be designated "normal galaxies" and will all be assumed to have the same dust-to-gas ratio and grain properties. A normal galaxy's emission in the *IRAS* bands is to first order a function of present stellar population (and therefore of initial mass function, star formation rate, and history), of spatial distributions of dust and stars, and of grain properties.

One purpose of this *Letter* is to reexamine the canonical simplification that, especially at 60 and 100 μm, *IRAS* measures directly the recent star formation rate in galaxies (Wynn-Williams 1982; de Jong *et al.* 1984; Soifer *et al.* 1984). This simplification approaches an exact statement for normal galaxies with a high current star formation rate, whose total luminosity is dominated by the far-infrared, e.g., for those undergoing starbursts. But most galaxies have less radiative output in the far-infrared than in the visible, suggesting a variable optical depth to the emerging ultraviolet radiation. Moreover, stars other than the youngest may contribute to heating the dust grains.

This *Letter* uses an approach based on the *IRAS* color-color diagram for galaxies (§ II) to discuss the decomposition of their emission into "natural" components. A phenomenological model involving two physical parameters is proposed as an improved interpretation of the far-infrared emission (§ III). The most important implication of the observations and model (§ IV) is that *IRAS* may measure poorly the recent star formation rate in galaxies in a quiescent phase.

II. THE COLOR-COLOR DIAGRAM

A scatter diagram of $R(60/100) = f_\nu(60\ \mu\text{m})/f_\nu(100\ \mu\text{m})$ versus $R(12/25) = f_\nu(12\ \mu\text{m})/f_\nu(25\ \mu\text{m})$ clearly demonstrates that galaxies require a superposition of several components to describe adequately their emission. Figure 1 shows that diagram for galaxies in *Cataloged Galaxies and Quasars Observed in the IRAS Survey* (1985) having high-quality fluxes in all four bands, and not flagged as extended, so the point source fluxes are an unbiased estimate of the total emission (*IRAS Explanatory Supplement* 1986 and *IRAS Small Scale Structure Catalog* 1986). Objects with $R(25/60) = f_\nu(25\ \mu\text{m})/f_\nu(60\ \mu\text{m}) > 0.18$ have been left out of Figure 1 and will not be considered further here because many (but not all) of them are dominated by a Seyfert nucleus (de Grijp *et al.* 1985). The remaining, "normal galaxies" spread out along a band such that the larger their $R(12/25)$, the smaller their $R(60/100)$.

The band corresponds to progressively greater star formation activity as it proceeds from the lower right-hand corner to the upper left-hand corner of the diagram. Three lines of evidence support this interpretation of the progression: First, Galactic cirrus (Low *et al.* 1984; Gautier 1986; Leene 1986) is found at the lower right end of the band, together with very quiescent spirals such as M31 (Walterbos 1986) and M81. In contrast, the upper left end is occupied by starburst galaxies like NGC 6240 (Wright, Joseph, and Meikle 1984), and blue compact dwarf galaxies or "extragalactic H II regions" such as Mrk 158, and compact Zwicky galaxies (Kunth and Sèvre 1986; Wynn-Williams and Becklin 1986). Second, both total infrared luminosity and infrared-to-blue ratio increase from lower to upper end of the band (de Jong *et al.* 1984; Kunth and Sèvre 1986). Third, tracks in the color-color diagram similar to the galaxy band are generated by models where a realistic mixture of grains including polycyclic aromatic hydrocarbons is subjected to increasingly intense radiation fields (Désert 1986).

The distribution of galaxies in a band in Figure 1 is not an artifact due to sample selection or the *IRAS* data processing. No selection effects could be identified that might generate this band by depopulating the surrounding regions in the

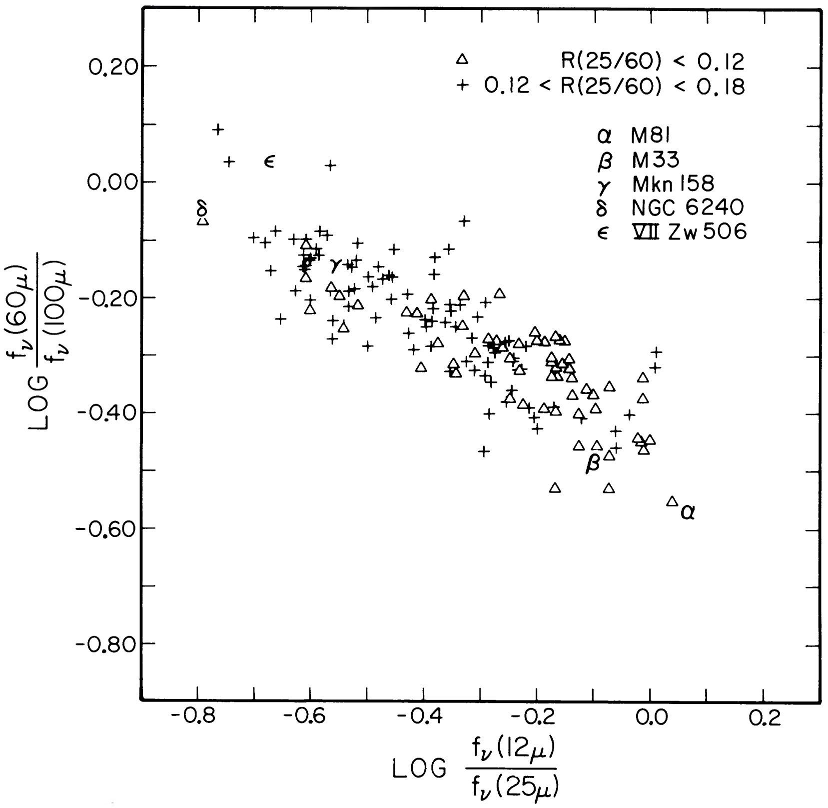

FIG. 1.—The *IRAS* color-color diagram for "normal" galaxies, with a few objects identified individually. The ratios plotted are formed between flux densities listed in the *IRAS Point Source Catalog* without color correction (*IRAS Explanatory Supplement* 1986).

color-color plane. All galaxies detected in three of the four *IRAS* bands have colors consistent with this distribution. Moreover, two other samples, both optically selected, confirm the reality of the band distribution as seen on Figure 1: (1) a sample of Virgo cluster spirals complete to a blue magnitude of 12.8 (Helou 1986), and (2) a sample of nearby galaxies, roughly complete to an apparent diameter of 10′ (Rice *et al.* 1986). However, in selecting only galaxies whose emission is unresolved by *IRAS*, a bias is introduced favoring high surface brightness objects and depleting the lower end of the band. This can be seen in a comparison of the distributions of $R(60/100)$ in the present sample and the Virgo spirals. The latter are substantially cooler as a population. The density of points in the diagram does not therefore reflect the frequency of occurrence of systems in an unbiased volume limited census.

III. PHENOMENOLOGICAL MODEL

The activity sequence thus established along the band has been recognized (Rowan-Robinson and Crawford 1986; de Jong 1987) as the result of mixing two components, denoted here by $C(\nu)$ for cirrus, and $A(\nu)$ for an active component related to H II regions. A galaxy travels up along the band as the ratio of active to cirrus contribution increases from $\ll 1$ to $\gg 1$. In the simplistic picture where the colors of both components are fixed, galaxies would distribute themselves along a single curve connecting the locations of A and C, and would not span the width of the band as observed. Variable extinction at 12 or 25 μm is quite unlikely to cause the scatter about that curve: at 12 μm extinction is only about 1 mag in the direction of the Galactic center, low enough to allow detection of 12 μm sources in the Galactic nucleus and beyond (Habing *et al.* 1985).

A natural assumption would be that while the colors of cirrus are constant, those of the active component are not, but depend to first order on the radiation intensity heating the dust in active regions, and therefore on gas density, initial mass function, and history. This assumption is the basis of the phenomenological model proposed here. Within this model, a galaxy's location in the color-color diagram is determined by two physical parameters: the intensity in its active regions and the ratio of active to cirrus contributions.

Constancy of the cirrus colors is a reasonable choice since the radiation field in the neutral medium averaged over a galaxy disk is relatively constant in intensity and composition among spirals. This choice is further supported by the fact that the large-scale (cosecant law) diffuse emission from the Milky Way has roughly the same colors as the small-scale cirrus fluctuations (Boulanger and Pérault 1986). For the present purposes, the cirrus component is identified with point X, which is consistent with available data, as shown on Figure 2. On the other hand, the dependence of *IRAS* colors on heating intensity is dictated by the presence of very small grains and by the emission features of polycyclic aromatic hydrocarbons at 7.7, 8.6, and 11.3 μm (Puget, Léger, and Boulanger 1985). This dependence is marked by the transition from the dominance of temperature fluctuations at low inten-

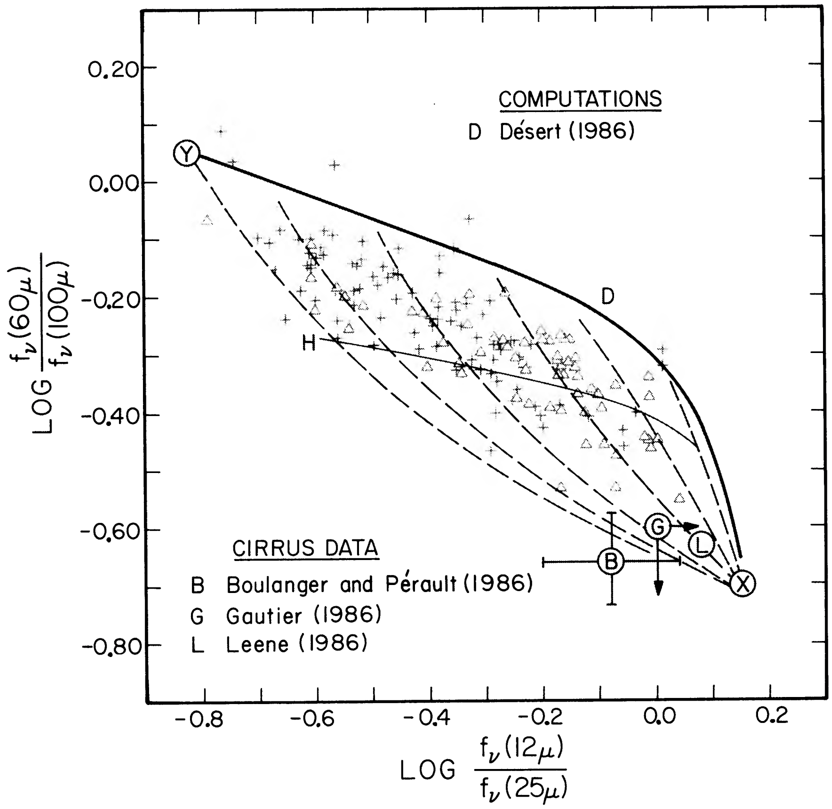

FIG. 2.—The phenomenological model compared to the normal galaxy data. Three measurements of cirrus are shown: Gautier's (1986) point is the boundary for the distribution of colors observed in a survey of filaments and clumps at high Galactic latitudes; Leene's (1986) colors are for the brightness of extended emission from part of the R CrA molecular cloud; Boulanger and Pérault (1986) obtain their ratios from a cosecant-law fit to the Galactic latitude profile of emission in each of the *IRAS* bands. Curves D and H are described in § III and § IV, respectively.

sity (Draine and Anderson 1985) to dominance by single temperature emission at high intensity, as is well illustrated by Désert's (1986) calculations of the emission from a distribution of dust grains comprising both normal and very small grains. Neglecting optical depth effects, Désert's calculations indicate that the emission traces out a curve like the one labeled D in Figure 2 as the ambient radiation field goes from solar neighborhood intensity (point labeled X) to several hundred times as much (point labeled Y). The overall character of curve D is quite stable, but its detailed shape depends on grain properties and size distributions. The particular curve D shown in Figure 2 provides an upper envelope for the galaxy data, and combines with the cirrus point (along dashed lines) to "predict" acceptable colors. The model can clearly account for almost all *IRAS* colors in the present sample of galaxies.

One of many possible tests of the model is provided by the prediction that the A component should correlate with tracers of recent star formation such as thermal radio or Hα emission and should do so better than the total far-infrared emission. Preliminary tests seem to confirm this prediction (Persson and Helou 1987).

IV. IMPLICATIONS

The most significant implication of the model is in quantifying the relation between far-infrared emission and the recent star formation rate in a galaxy. In the simplest approach to obtaining this rate, the *IRAS* data must first be decomposed to get $A(\nu)$, the spectral distribution of the infrared emission from the active regions. The *stellar* luminosity in active regions, L_A, is then deduced from A using:

$$L_A = 4\pi d^2 \int A(\nu)\, d\nu / [1 - \exp(-\tau_A)], \qquad (1)$$

where d is the distance to the galaxy, and τ_A is the effective optical depth associated with A. Finally, the conversion of L_A into a mass rate can be done once a stellar mass function is assumed.

The fraction of infrared emission directly contributed by the active component can be estimated using the phenomenological model in § III. For a given galaxy, this fraction is deduced from position in the color-color diagram, and varies from 0 to 1 as the galaxy moves from point X toward curve D. Objects lying on curve H in Figure 2 have that fraction equal to $\frac{1}{2}$, so for galaxies below H the total infrared flux cannot be interpreted as due to current star formation. For most objects in Figure 1 that fraction is reasonably close to 1, but the selection of these objects is biased (§ II), and the bulk of normal galaxies will probably lie below curve H.

Values of τ_A and stellar mass function will both vary as an active region travels along curve D. The most active galaxies (upper left end of curve D) display high infrared-to-blue ratios, indicating $\tau_A \gg 1$; they are also most likely to have ongoing star formation. Thus in these galaxies, the luminosity in A equals the luminosity in young stars, and the star formation rate can be evaluated using an initial mass function. Further to the right on curve D where the mean H II region is more diffuse, τ_A will certainly decrease, and the stellar mass function will be older on average. These variations will add substantial uncertainty to the estimation of L_A and the star formation rate, which uncertainty could be reduced if a physical sequence of H II regions were associated with curve D.

The cirrus component C is certainly due in large part to older disk stars. Boulanger and Pérault (1986) estimate at least half of the cirrus emission in the solar neighborhood is reradiated from stars older than 10^8 yr. Possible variations in this fraction (which depends in detail on grain properties) and the very uncertain optical depth offered by cirrus to the ambient radiation (galaxies with cool cirrus-like colors tend toward low infrared-to-blue ratios) will frustrate any effort to recover the heating luminosities for this component. Dusty galaxies devoid of young stars could also exist whose far-infrared emission has only the C component, completely at odds with an interpretation in terms of current star formation.

V. CONCLUSIONS

In the *IRAS* color-color diagram, "normal" galaxies appear along a band populated continuously from the quiescent, cirrus-like end to the active, starburst end. While more work is required to quantify the relation of recent star formation rate to far-infrared emission, the data demonstrate clearly that emission from some galaxies is dominated by cirrus, and from others by recent star formation. This alone should discourage the statement that far-infrared luminosity is simply proportional to the number of massive young stars in a normal galaxy. While the statement is correct for many galaxies, it is wrong by uncertain and varying amounts for the others.

Finally, given the two extreme possibilities of the far-infrared luminosity being dominated either by cirrus or by young stars, the close relation between far-infrared and nonthermal radio emission in galaxies becomes even more intriguing as it seems to apply independent of *IRAS* color (Helou, Soifer, and Rowan-Robinson 1985). The case of galaxies dominated by cirrus reinforces the argument that the nonthermal radio is due primarily to synchrotron emission by cosmic-ray electrons.

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