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## 1. INTRODUCTION

In this review I shall be mainly concerned with the ways in which recent infrared observations, particularly by IRAS, have influenced our ideas about star formation in "normal" galaxies.

## 2. IRAS SURVEYS AS A POINTER TO STAR FORMATION

That strong infrared emission is common in spiral galaxies became clear at the time of publication of the first group of IRAS papers. De Jong et al. (1984) examined a sample of 165 galaxies in the Shapley-Ames catalog and found that over 80% of spirals (Sa and later) were detected by IRAS, though none of the ellipticals were seen. Since the publication of the IRAS point source catalog it has been possible to examine the incidence of infrared emission from galaxies on a proper statistical basis. The infrared luminosity function has been calculated by several groups (Lawrence et al. 1986; Soifer et al. 1986; Rieke and Lebofsky 1986). In general it resembles that of galaxies at visible wavelengths except that there appears to be an excess of sources with luminosities above about $10^{10}$ $L_{\odot}$. These high luminosity objects include active galaxies and "starburst" galaxies that will be receiving much attention elsewhere in this volume. I will generally be discussing lower-luminosity spiral galaxies in this paper, although I will present evidence that a number of early-type barred spiral galaxies may be exhibiting signs of low-level nuclear activity.

A crucial problem in trying to use infrared luminosities as a guide to star formation activity in galaxies is the difficulty of distinguishing emission from the diffuse interstellar medium and emission from dust heated by newly formed or still-forming stars. Attempts have been made to use various flux ratios for this purpose. de Jong et al. (1984) found that the ratio $L_{IR}/L_B$ increases with the 60-100 μm color temperature. From this result has come the idea that spiral galaxy disks contain a cool dust component that corresponds to the diffuse or "cirrus" emission, plus a warmer component that dominates in cases of galaxies that are undergoing large amounts of star formation.

The separation of the infrared emission into a "cirrus" and a star formation component may be tested by comparing the IRAS data with some independent parameter, such as the Hα or the CO fluxes. The results are not conclusive. Two groups have compared the IRAS fluxes from a number of spiral galaxies with the star formation rates calculated by Kennicutt from measurements of Hα spectrophotometry; Moorwood, Veron-Cetty, and Glass (1986) conclude that the infrared emission from Kennicutt's galaxies matches that expected on the basis of Hα emission from star formation regions, but Persson and Helou (1986) conclude that the bulk of the infrared emission from these galaxies comes from the interstellar "cirrus" component. Young (1986) finds a correlation between infrared luminosity and the luminosity in the 2.6 mm CO line, supporting the idea that much of the infrared emission is associated with star formation. Since some of the galaxies in her study are of very high luminosity, however, the result does not necessarily apply to "normal" galaxies.

A challenge to the idea that the 60-100 μm color temperature is an indicator of the role of star formation in galaxies has been raised by Burstein and Lebofsky (1986). They present evidence that the apparent far-infrared luminosity of Sc galaxies varies with inclination. This result would imply that the disks of these galaxies are optically thick at 100 μm, which in turn would require that the emission be concentrated within the central 1 kpc diameter region. Burstein and Lebofsky's conclusions are disputed by Rice, Elias, and Persson (1986), who point out that problems arise due to the difficulties of correctly classifying galaxies that have high inclinations. Another difficulty with Burstein and Lebofsky's hypothesis is that Devereux, Becklin and Scoville (1986) found that the emission from most Sc galaxies is not concentrated within the central 1 kpc, at least at 10 μm.

The strongest correlation that has appeared so far from the IRAS data is the very close proportionality between the 60 μm flux density from warm dust and the centimeter-wavelength nonthermal emission (de Jong et al. 1985; Helou, Soifer, and Rowan-Robinson 1985). This correlation has not yet been satisfactorily explained. One popular model has it that the radio emission is dominated by synchrotron emission from individual supernova remnants and that both the infrared luminosity and the supernova rate are proportional to the star formation rate. A problem with this model is that in the two cases where adequate data are available, namely M82 (Kronberg et al. 1985) and the Galaxy, individual supernova remnants are responsible for only a small fraction of the total synchrotron emission from the galaxy disk. In an alternative model the radio emission originates from relativistic electrons in the general interstellar medium. The difficulty with this model is that synchrotron emission depends strongly on the magnetic field strength as well as the number density of relativistic particles. To explain the proportionality of infrared and radio emission it is necessary to identify a mechanism that controls the interstellar magnetic field strength in various different star-forming regions. As yet no such mechanism has been identified.

## 3. DEPENDENCE OF STAR FORMATION RATE ON HUBBLE TYPE

The principle of the Hubble classification of spiral galaxies is that the bulge-to-disk ratio is higher in early-type galaxies (Sa-Sb) than in late-type galaxies (Sc-Sd). The ratio of the current to the historical star formation rate is higher in late-type galaxies than early-type galaxies (Kennicutt 1983).

Devereux, Becklin, and Scoville (1986) present evidence that the IRAS emission from spiral galaxies is mainly a disk phenomenon. They find that their measurements of the 1.65 μm nuclear (5.5 arcsec or 500 pc diameter) flux densities of Virgo cluster spirals is much better correlated with the 60 μm flux densities in disk-dominated late-type spirals than in bulge-dominated early-type spirals. On the whole, however, the dependence of infrared luminosity on Hubble type is weak for spiral galaxies. Devereux (1986) finds no statistically significant differences between the fractional luminosity functions of galaxies of Hubble types in the range Sa to Sc, though there appear to be deficiencies of high-luminosity galaxies in the very late and very early classes. There are strong resemblances between the infrared fractional luminosity function and the radio continuum fractional luminosity function of spiral galaxy disks, as derived by Hummel (1981).

The 60-100 μm color temperature shows more dependence on Hubble type than does the bolometric luminosity. Table I summarizes an analysis by Devereux (1986) of a sample consisting of all 227 known galaxies in the distance range 15-40 Mpc, the galactic latitude range $|bII| > 20°$, and with a 60 μm luminosity $(\nu S_\nu) > 2 \times 10^9$ $L_\odot$. There is a statistically significant excess of "hot" galaxies among early types. He has also measured the "compactness" of many of the sample galaxies at 10 μm by comparing the flux in a 5.5 arcsec IRTF beam with the color-corrected 12 μm flux measured through the much larger IRAS beam. He finds that galaxies in which the 10 μm emission is compact are significantly more common among early-type than among late-type galaxies. A similar result was found by Hummel (1981) for the central radio sources of disk galaxies, but observations in the 2.6 mm CO emission line show a different trend with a number of early-type galaxies displaying a central hole rather than an enhancement (Young 1986).

Table I
Classification of 227 Nearby Galaxies
by Hubble Type and by 60-100 μm color temperature

| | "Hot" >44 K | "Cold" <44 K |
|---|---|---|
| Early (S0/a-Sb) | 35 | 49 |
| Late (Sbc-Sm) | 25 | 118 |

## 4. ROLE OF BARS

The first evidence that the infrared properties of galaxies were affected by the presence of bars was presented by Hawarden et al. (1986), who showed that a number of barred galaxies exhibit an energy distribution that is characterized by high 25μm/12μm and low 100μm/25μm flux density ratios. They estimated that over 30% of barred luminous galaxies show a flux excess at 25 μm and attributed this excess flux to a circumnuclear region of intense star formation.

The sample analyzed by Hawarden et al. includes only galaxies that have 12 μm and 25 μm flux densities above the IRAS point source catalog limit. Devereux (1986) has examined the effect of bars in the somewhat larger volume-selected sample of galaxies that was defined in section 3. He finds that the effect of bars is much more important in early-type galaxies than in late-type galaxies. He finds that most of the early-type galaxies exhibiting high compactness are barred, as are 29 of the 35 galaxies in the "hot" and "early" class in Table I. This work is described in more detail elsewhere in this volume.

On a smaller scale, aperture synthesis observations in the 2.6 mm CO line have provided evidence for bar-like structures of molecular material in the inner regions of IC 342 (Lo et al. 1984) and NGC 6946 (Ball et al. 1985).

## 5. COMPACT AND DWARF GALAXIES

Many galaxies for which there was preexisting evidence for nuclear (or, at least, localized) rapid star-forming activity are strong IRAS sources. These include many of the non-Seyfert Markarian galaxies and the compact blue "H II region" galaxies like II Zw 40. A large number of papers incorporating IRAS observations have recently appeared (Gondhalekar et al. 1986; Hunter et al. 1986; Klein et al. 1986; Kunth and Sevre 1986; Sramek and Weedman 1986; Thronson and Telesco 1986; Wynn-Williams and Becklin 1986). The IRAS observations generally confirm that these galaxies have high star formation rates. Specifically, Kunth and Sevre (1986) find that blue, compact emission-line galaxies generally have higher IR/blue flux density ratios and higher 60μm/100μm color temperatures than spiral galaxies in the Shapley-Ames catalog.

## 6. ELLIPTICAL AND SO GALAXIES

Very few ellipticals were detected in the IRAS survey. A higher success rate was achieved by Impey, Wynn-Williams, and Becklin (1986), who looked for 10 μm emission from a sample of 65 bright elliptical galaxies using a 5.5 arcsec beam on the IRTF. One third of the sample showed emission above that expected from pure photospheric emission, but this emission is more likely to arise from circumstellar shells around late-type giant stars than from regions of current star formation.

SO galaxies are much more common in the IRAS catalog than are ellipticals. Devereux, Becklin, and Scoville (1986) found that 7 out of 34 SO galaxies in the Virgo cluster were detected by IRAS. The 60μm/100μm color temperatures of these galaxies are similar to those of normal spirals, which led Becklin (1986) to suggest that star formation may be the source of luminosity in these galaxies. However, their radio continuum emission (Hummel and Kotanyi 1982) appears to be lower than would be expected from an application of Helou, Soifer, and Rowan-Robinson's (1985) radio/infrared relation to the measured IRAS fluxes.

## 7. STUDIES OF INDIVIDUAL REGIONS

Future progress in understanding star formation in galaxies will require detailed studies of individual regions as well as a statistical examination of suitably chosen samples. Very few galaxies have angular sizes large enough that they can be mapped by IRAS. M31 has been described by Habing et al. (1984); a few others, including M33, are being presented by Walter Rice (this volume). Wainscot, de Jong, and Wesselius (1986) have used the chopped photometric channel on IRAS to produce scans along the disks of several edge-on galaxies. In the case of NGC 891 they find good agreement among the 50 μm, 21 cm continuum, and CO profiles, all of which are considerably narrower than the 21-cm H I emission.

The best far-infrared resolution achieved to date on an extragalactic source is the study of the central regions of M51 by Lester, Harvey, and Joy (1986) using a 24 arcsec slit in the Kuiper Airborne Observatory. They find that much of the far-infrared luminosity of this galaxy comes from a small, sharply bounded region within a 700 pc radius of the nucleus. Finer detail than this can only be achieved by moving to shorter wavelengths and using large ground-based telescopes such as the IRTF. Maps at 10 μm of the central regions of galaxies such as NGC 2903 (Wynn-Williams and Becklin 1985), and NGC 3310 (Telesco and Gatley 1984) tend to show agreement in general, but not in detail, between the regions of strongest radio, infrared, and optical emission. Much more mapping at infrared wavelengths will be needed to disentangle the effects of dust extinction and of variations in the stellar formation histories in these regions.

Infrared spectroscopy is another area where important contributions can be expected from ground-based observations in the next few years. Roche and Aitken (1985) have shown that the 8-13 μm spectra of spiral galaxy nuclei show much stronger 11.6 μm features than are seen in H II regions in our Galaxy. It remains to be seen whether this effect is also seen in extragalactic spiral-arm star formation regions.

## 8. UNANSWERED QUESTIONS

I conclude with a list of questions I think we need to address before claiming to understand the nature of infrared emission from normal galaxies.

- Is there a fundamental difference between normal and "starburst" galaxies?
- What is the best way to separate "cirrus" emission from emission from star-forming regions?
- Do measurements of visible H II regions provide a reliable guide to the current star formation rate?
- Is the far-infrared optical depth in spiral galaxy disks large enough to produce self-absorption at high inclination?
- Does the radio emission come from supernova remnants or from cosmic rays in the interstellar medium?
- What is going on in early-type barred galaxy nuclei?
- Is there star formation in S0 galaxies?
- Do star formation conditions in the central regions of spiral galaxies resemble those in the disks?

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## DISCUSSION

ELMEGREEN:

Early-type bars are different from late-type bars with respect to brightness profile, relative size and kinematics (Elmegreen and Elmegreen 1985, *Ap.J.*, **288**, 438). The early-type bars apparently contain inner Lindblad resonances and inner spirals, whereas the late-type bars may end at the ILR and contain no additional resonances. The inner spirals in early-type barred galaxies are modeled by Sanders and Tubbs (1980, *Ap.J.*, **235**, 803) and others as pure-gas spiral shocks, responding to the inner resonances. Apparently these spiral shocks promote unusually high star formation rates. This would explain the effect described by Hawarden *et al.*, but in addition, why early early-type galaxies show it more than late types.

YOUNG:

I think it is important to clarify the use of the term 'starburst.' A galaxy which is luminous in the IR and has a high $H_2$ mass may simply be a scaled-up version of the Milky Way, while a lower luminosity galaxy which has very little $H_2$ may be very efficiently forming stars. What is your definition of starburst?

WYNN-WILLIAMS:

I am not particularly fond of the term. I expect Dan Weedman will provide us with a definition of it tomorrow.

FROGEL:

You showed a viewgraph which indicated that a larger fraction of early-type galaxies have a warm dust component than late-type galaxies. According to Mezger's bimodal model, early types would have more star formation than late types. This appears to contradict widespread belief that late-type galaxies are more active. Would you please comment on this.

WYNN-WILLIAMS:

The galaxies with a warm dust component tend to be early-type barred galaxies and there is evidence that this extra component is associated with the central regions rather than the disk.