

## BURSTS OF STAR FORMATION IN GALAXIES

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**ABSTRACT.** A minority of spiral galaxies is currently undergoing bursts of intense star formation. This paper reviews studies that have been made of these galaxies at visible, radio, and infrared wavelengths, with an emphasis on results that have emerged since the IRAS survey.

### 1. INTRODUCTION

It has been known for more than ten years that the centers of certain galaxies contain regions of very active star formation. In at least some of these galaxies the activity has been established to be transitory because of the impossibility of supplying sufficient interstellar gas to sustain the observed rate of star formation over a Hubble lifetime. The regions of very active star formation that I shall be discussing in this talk are found within a few hundred parsecs of the nuclear regions of certain spiral galaxies. I shall not be discussing rapid star formation in irregular galaxies, though such activity is certainly seen in blue dwarfs like IIZw40, (e.g., Thuan 1983) and the "clumpy" irregular galaxies like Mkn 297 (e.g., Heidmann et al. 1982).

The word "starburst" is often used to describe galaxies which are currently undergoing a bout of rapid star formation. Various authors have tried to apply a quantitative definition to the word based on some criterion such as bolometric luminosity, color, or infrared surface brightness. Such definitions are useful when results of a statistical nature are being discussed. As yet, however, there has been no convincing demonstration that any well-defined qualitative property exists that unambiguously separates "starburst" from "normal" galaxies. In this review I shall therefore dodge the issue of how, if at all, we should define "starburst" galaxies in ambiguous cases and will focus instead on what has been learned from the study of more or less clear-cut examples of the phenomenon.

## 2. VISIBLE-WAVELENGTH STUDIES

As far as I know the word "starburst" was first used in print by Weedman et al. (1981) in the context of the galaxy NGC 7741, but the existence of the phenomenon had been inferred earlier. An important primary source for visible-wavelength work on starburst galaxies is the Markarian survey (e.g. Markarian et al. 1980) which picked out galaxies with an ultraviolet excess. The work of Huchra (1977) established that while a few Markarians are Seyferts or other exotic objects, most are galaxies whose blue color is caused by the presence of more than the usual number of young stars.

The most methodical visible-wavelength study of starburst galaxies is that of Balzano (1983). She selected a sub-sample of 102 Markarian and emission-line galaxies that had stellar or semi-stellar nuclei but showed no Seyfert character. Among the conclusions of her study were

- Emission-line ratios for starburst regions are like those of low-excitation H II regions.
- About 3% of galaxies in the magnitude range  $-17.5 > M_V > -22.5$  have starbursts.
- Starbursts are often found in interacting systems.

Although Balzano's selection criteria have defined a very useful sample of starburst galaxies, several important classes are omitted. Among them are galaxies with nuclear regions that are obscured at visible wavelengths, galaxies with a combination of starburst and Seyfert activity, and galaxies in which the star formation regions are significantly resolved by the telescope. An important component of the latter category are the "hot-spot" galaxies discussed by Morgan (1958) and Sersic (1973).

## 3. RADIO-WAVELENGTH STUDIES

The VLA study by Condon et al. (1982) was an important turning point in the study of starburst galaxies. The work was focussed on a sample of galaxies with an unusually high ratio of radio to blue flux density as determined in the earlier Arecibo survey of bright spiral galaxies by Dressel and Condon (1978). From their data on 33 galaxies they concluded that

- Radio emission from these galaxies comes predominantly from an extended central region a few hundred parsecs across that is usually extended in the plane of the galaxy.
- The radio emission is mainly of non-thermal (synchrotron) rather than thermal (free-free) origin.

The question of whether the non-thermal emission in these regions

should be attributed to a cosmic ray background or to individual supernova remnants will be discussed in Section 7.

#### 4. PRE-IRAS INFRARED STUDIES

Infrared emission from heated dust is found in a significant fraction of spiral galaxies and in essentially all galaxies that show signs of starburst activity at visible and radio wavelengths (e.g., Rieke and Lebofsky 1978; Smith 1984). Far-infrared observations are particularly important because they provide the only reliable way of determining the bolometric luminosities of the star-forming regions of these galaxies.

Before the IRAS survey, data in the 30-300  $\mu\text{m}$  range were available for only about a dozen galaxies (e.g., Telesco and Harper 1980), although 10  $\mu\text{m}$  ground-based observations had been made of more than a hundred (e.g., Rieke and Lebofsky 1978; Cizdziel et al. 1985; Scoville et al. 1983a). Among the general results found were the following:

- To first order the infrared energy distributions of spiral galaxies resemble those of Galactic H II region/molecular cloud complexes.
- Much of the emission is from dust at around 50 K, but there is evidence for an extra component of emission at around 10  $\mu\text{m}$  that probably arises from temporarily heated microscopic grains (Wynn-Williams and Becklin 1985).
- Galaxies powered by star formation tend to have lower far-infrared color temperatures than those with Seyfert nuclei.
- In at least a few galaxies there is a correspondence in general, though not in detail, between the spatial distributions of the 10  $\mu\text{m}$  and the radio emission (e.g., Rieke et al. 1980; Wynn-Williams and Becklin 1985).

Airborne photometry established that the central regions of "starburst" galaxies could generate luminosities in the range  $10^{9.5}$  to  $10^{10.5} L_{\odot}$ . Several authors have investigated what sorts of model starburst could account for this power. As first pointed out by Rieke et al. (1980) the mass-to-light ratios of some starburst regions are lower than that produced by a Salpeter-like initial mass function. A favored explanation for this result is that the stars formed during the starburst are predominantly of high mass, and hence, low mass-to-light ratio. Gehrz et al. (1983), for example, estimate that in NGC 3690 more than  $10^9 M_{\odot}$  of stars with mass  $>6 M_{\odot}$  are formed within  $10^8$  years.

#### 5. IRAS OBSERVATIONS OF GALAXIES

Approximately 20,000 extragalactic objects were detected by the IRAS survey (1985). Of these about 6,000 are identifiable with previously catalogued galaxies in the Uppsala and other published catalogues.

Almost all the remainder are identifiable as 15th magnitude or fainter galaxies on the Palomar Sky Survey. Most of those sources previously described as unidentified have now been recognised as faint galaxies (Houck et al. 1985). Most galaxies in the IRAS catalog are spirals, although only a few are Seyferts. Most of the extragalactic objects in the IRAS catalog were detected only in the 60 and 100  $\mu\text{m}$  channels. Ground-based studies of galaxies in the preliminary IRAS lists have been published by Allen et al. (1985), Moorwood et al. (1985) and Elston et al. (1985).

The sixth preliminary list of IRAS sources comprises a "mini-survey" of about 900 square degrees of sky to about the same sensitivity as the final survey (Soifer et al. 1984). In that region 86 sources were identified as galaxies. The ratio of luminosity at infrared and blue wavelengths (expressed as  $v_{S_V}$  at 80  $\mu\text{m}$  and B) ranges from 0.3 to 30 for this sample. These values are higher than those of many "traditional" starburst galaxies and imply a very efficient conversion of light to infrared. There is a slight tendency for the more luminous galaxies to have a hotter 60  $\mu\text{m}$ /100  $\mu\text{m}$  color temperature, suggesting that a starburst produces hotter dust than is found in the disks of normal galaxies.

Spectra have been obtained for most of these galaxies either at Palomar or at Mauna Kea; almost all show H II region-like emission-line spectra from which redshifts can be obtained. The median distance of the objects is about 100 Mpc, assuming  $H = 75 \text{ km/sec/Mpc}$ . Luminosities are mostly in the range  $10^{10}$  to  $10^{11} L_{\odot}$ . For comparison we may note that

- The infrared luminosity of the classic starburst galaxy M82 is  $3 \times 10^{10} L_{\odot}$  (Telesco and Harper 1980).
- The typical infrared luminosities of normal spirals, as determined by Devereux (1986) for a complete sample of galaxies in the distance range 20–40 Mpc, are in the range  $10^9$ – $10^{10} L_{\odot}$ .
- The IRAS luminosities of the "mini-survey" galaxies are similar to those of Balzano's (1983) optically selected galaxies.

As would be expected for a flux-limited sample, therefore, the "mini-survey" galaxies are strongly biased towards sources of higher than normal luminosity. On further examination many of these will probably turn out to be starburst galaxies. It must be remembered, though, that high infrared luminosity is neither a necessary nor a sufficient condition for a galaxy to be a starburst. The dwarf galaxy IIZw40, whose visible emission is totally dominated by light produced as a result of current star formation, has an IRAS luminosity of  $2 \times 10^9 L_{\odot}$ , weaker than all but one of the mini-survey galaxies (Wynn-Williams and Becklin 1986).

## 6. SIZES OF STARBURST REGIONS

Although starburst regions give out most of their power in the 50–200  $\mu\text{m}$  region, little spatial information is available at these wavelengths, because of poor telescope resolution. Mapping is therefore usually performed at 10–20  $\mu\text{m}$  wavelength. Galaxies that have been mapped include M82 (Rieke et al. 1980), IC 342 (Becklin et al. 1980), NGC 253 (Rieke and Low 1975) NGC 1068 (Telesco et al. 1984), and NGC 2903 (Wynn-Williams and Becklin 1985). Approximate sizes have been determined for several more (Rieke 1976). Generally speaking, fair agreement is found between the sizes and shapes of the radio and infrared emitting regions, though differences in detail certainly exist. In the case of M82 we also have a map of the 2.6 mm CO emission (Lo et al. 1986); it agrees well with the radio and 10  $\mu\text{m}$  emission.

Most IRAS galaxies are too faint to map at 10–20  $\mu\text{m}$ , but we may obtain a rough idea of their sizes by comparing 1 arcmin resolution IRAS fluxes with small beam photometry in the nearby ground-based windows. At Mauna Kea, Eric Becklin, Gary Hill, and myself have used the IRTF at 10  $\mu\text{m}$  to make this comparison for a number of galaxies in the 4th and 6th preliminary IRAS lists. We have found that a significant fraction of the galaxies have a characteristic scale size in the 500–1000 pc range. It is encouraging that these scale size are comparable to those seen in the "classical" starburst galaxies, but because our sample may be affected by selection effects this result should be regarded as rather tentative.

## 7. THE RADIO-INFRARED CONNECTION

A linear relationship between 10  $\mu\text{m}$  thermal dust emission and centimeter-wave non-thermal radio emission from galaxies was first noticed by van der Kruit (1971) and by Rieke and Low (1972). The advent of IRAS has permitted the radio-infrared relation to be examined in the crucial 60–100  $\mu\text{m}$  band, and de Jong et al. (1985) and Helou et al. (1985) have both demonstrated that the ratio between radio and infrared emission is the same for both starburst nuclei and for spiral galaxy disks, and that the relationship holds both for apparent fluxes and for absolute luminosities.

There is currently no agreement as to the origin of the radio emission. Rieke et al. (1980) and others have argued that the emission arises from individual supernova remnants. Points in favor of this hypothesis are:

- The linearity of the radio-infrared relation is explained if both bolometric luminosity and supernova rate are proportional to the star formation rate.
- M82 has a number of compact variable radio sources that are probably supernova remnants of some kind. (Kronberg and Sramek 1985; Kronberg et al. 1985).

Alternatively, the radio emission may arise from the interaction of cosmic ray electrons with the interstellar magnetic field in the starburst region. Points in favor of this view are

- In both M82 and our Galaxy the bulk of the non-thermal emission is diffuse rather than identifiable with discrete supernova remnants (SNRs).
- The compact sources in M82 differ markedly from SNRs in the Galaxy in their luminosities and decay rates. This result implies that the total emission from SNRs in a galaxy must depend on more factors than just the star formation rate.
- The strength of the radio emission can only be explained in terms of individual SNRs if a very high rate of supernova formation is assumed (Helou et al. 1985).

The main problem with the "diffuse" theory is that it does not provide any obvious explanation for the proportionality between radio and infrared emission. The strength of synchrotron emission depends on the local magnetic field, and in a region of interstellar space as confused as a starburst region this field must be particularly hard to predict. The fact that the linear relationship exists suggests to me that it might be worth exploring the possibility that some kind of equilibrium could be established between the stellar radiation energy density and the magnetic field energy density in one or more phases of the interstellar medium.

## 8. CAUSES OF STARBURSTS

Two circumstances have been identified that appear to be particularly conducive to the initiation of a starburst. These are interactions between galaxies and the presence of a bar in a galaxy.

Larson and Tinsley (1978) showed that interacting galaxies have a large spread in UBV colors indicative of the presence of star formation on time scales of the order of the interaction time. Subsequently, Balzano (1983) found that about half of her "starburst" galaxies are in interacting systems. Most recently has come direct evidence that strong infrared emission is a common property of interacting galaxies. The evidence comes from IRAS observations (Lonsdale et al. 1984), as well as 10  $\mu\text{m}$  observations with small beams (Joseph and Wright 1985; Cutri and McAlary 1985). It is also true that strongly interacting galaxies have an increased tendency to harbor Seyfert nuclei (Dahari 1985). The probable mechanism whereby interactions enhance nuclear activity is tidal disruption that causes interstellar matter to fall inwards and increase the fuel supply for new stars. Gaskell (1985) has proposed a variant of this mechanism in which much of the disruption of one galaxy is caused by dwarf companions of the other.

Hawarden et al. (1985) have produced good evidence that the presence of a bar in a galaxy increases the probability that it will have

infrared colors characteristic of a starburst. Devereux (1986) has extended this work and shown that among a volume-limited sample of all galaxies with  $L_{\text{IR}} > 10^{9.5} L_{\odot}$  the ratio of barred to unbarred galaxies is several times higher among galaxies with "hot" 60/100  $\mu\text{m}$  color temperatures than among colder galaxies. He also finds that bars are significantly more common among galaxies with infrared luminosities above  $10^{10} L_{\odot}$  than among less luminous galaxies. Aperture synthesis maps of CO emission from some "classical" starburst galaxies such as NGC 6946 (Ball et al. 1986) show that bar structures can also exist in molecular gas.

## 9. STARBURSTS AND NON-STELLAR NUCLEAR ACTIVITY

An interesting number of cases are known in which there are associations between starbursts and non-stellar nuclear activity. Several Seyfert galaxies are known in which the active nucleus is surrounded by a region of intense star formation. In NGC 1068, a type 2 Seyfert galaxy, half of the total infrared luminosity, namely about  $1.5 \times 10^{10} L_{\odot}$ , comes from a 3 kpc diameter region that is also seen as a blue visible disk and a molecular ring (Telesco et al. 1984; Scoville et al. 1983b). In NGC 7469, a type 1 Seyfert, the nucleus is surrounded by a region that produces strong millimeter-wave CO emission, 3.3  $\mu\text{m}$  dust emission, clumps of narrow-line emission, and diffuse radio emission (Heckman et al. 1986). Both these galaxies show H<sub>2</sub> emission at 2  $\mu\text{m}$ .

NGC 6240 is a galaxy which has been hailed as a "super starburst" by several authors (e.g., Rieke et al. 1985), on account of its high infrared luminosity ( $4 \times 10^{11} L_{\odot}$ ). It has a 1.6 arcsec separation (800 pc) double nucleus at both radio and visible wavelengths and a distorted outer morphology; it may represent a merger between two galaxies. Depoy, Becklin, and Wynn-Williams (1986) have performed 1.8-4.2  $\mu\text{m}$  spectroscopy on NGC 6240 on the United Kingdom Infrared Telescope and have found that the galaxy has properties that indicate that something more than pure star formation is going on. The B $\gamma$  and P $\alpha$  hydrogen recombination lines are much weaker than in other starburst galaxies; we infer that normalized to their bolometric luminosities there is ten times less ionizing radiation, and therefore 0 stars, in NGC 6240 than in M82. The lines of molecular hydrogen, on the other hand, are extremely strong; about 0.35% of the bolometric luminosity of the galaxy emerges in shock-excited molecular hydrogen lines. It appears very probable that NGC 6240 harbors something more than a starburst--perhaps an obscured active nucleus.

## 10. UNANSWERED QUESTIONS

The study of starburst galaxies is still at an early stage. In the next few years I would hope that some of the following questions will be answered.

- Are interactions and bars the only triggering mechanisms?

- What sets the sizes of the starburst region?
- How does the initial mass function vary in starburst galaxies, and how do we suppress the low-mass stars?
- Why is the radio/infrared proportionality so narrow?
- Is there a causal connection between starburst activity and non-stellar nuclear activity

## 11. ACKNOWLEDGEMENTS

I thank Eric Becklin, Darren Depoy, Nick Devereux, and Gary Hill for many fruitful discussions. This work was supported under NSF grant AST 84-18197.

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SOLOMON: 1) What fraction of the total luminosity of all spiral galaxies is in the far IR? 2) What is the size of the region containing most of the far IR?

WYNN-WILLIAMS: 1) The IR to blue flux ratio varies greatly among spiral galaxies. I do not know of a calculation that has treated the ratio statistically in the way you suggest. 2) See Harvey's reply.

DOWNES: What is the evidence that some of the 2  $\mu\text{m}$  radiation in some of these galaxies may be due to a young population rather than an old one?

WYNN-WILLIAMS: This issue is quite controversial. The very young 2  $\mu\text{m}$  emission from some very luminous IRAS galaxies suggests to some people that the 2  $\mu\text{m}$  emission may be associated with a starburst.

THOMPSON: The low Br $\gamma$ /H $_2$  flux in NGC 6240 seems to indicate shocked H $_2$  due to galactic collisions rather than star formation as you stated. It is not clear, however, that we know this ratio integrated over our own galaxy. Does anyone have a good measure of this?

WYNN-WILLIAMS: It would be most interesting to have this ratio, but I do not know of any attempt to estimate it.

OKUDA: Do you think that the IRAS galaxies are a new type of galaxies not previously known?

WYNN-WILLIAMS: Most of them appear to be closely related to galaxies we already know about, but since only a small fraction of IRAS galaxies have been studied in detail it is too early to give a definite answer.

SILK: 1) What is the minimum duration of the starburst phenomenon? This is crucial in order to make any given inference about a possible deficiency in low mass stars; since reducing the burst-time duration could go in the direction of weakening such a conclusion

2) Can spectroscopic indicators (e.g. the 2  $\mu\text{m}$  CO band) be used to determine a minimum age?

WYNN-WILLIAMS: 1) Estimates of the duration of starbursts are not reliable at the moment. 2) It is difficult to distinguish giants from supergiants by means of the 2  $\mu\text{m}$  CO band, so the use of this band for age determination is not very promising.

PUDRITZ: Has there been any work done on the correlation of X-ray with infrared properties or IRAS starburst galaxies?

WYNN-WILLIAMS: Nothing has yet been published, though I know that several groups are looking into this.

WILLNER: What is the space density of the IRAS selected galaxies? How does it compare with that of the Bolzano sample?

WYNN-WILLIAMS: Weedman (BAAS 17, 846) has estimated that twice as many starburst systems are discernible by their 60  $\mu\text{m}$  continuum as by their excess ultraviolet continuum.

HARVEY: In answer to several questions about sizes of the far-infrared sources in galaxies; for one starburst galaxy, we have an upper limit to the size at 50 and 100  $\mu\text{m}$  of 7" - 8" which is a couple kiloparsecs.

ALLEN: I would like to add a note of caution about attaching too much weight to these "global" correlations, such as the correlation between radio continuum flux density and infrared flux for a large sample of galaxies which you have reviewed, and also the correlations among the radial distributions of various components in galaxies as reviewed by Judy Young previously. I think *most* of these correlations

are due to a "richness" effect; bigger galaxies have more of everything, and it does not all necessarily have to be causally related in any immediate way. By the way, Hummel showed nearly ten years ago that there is an equally "tight" correlation between the radio continuum flux density of a large sample of galaxies and their blue light; however, not more than a small fraction of either has anything directly to do with recent star formation.

YOUNG: I have chosen not to stress the correlations with the radio continuum, since I think of all the components discussed, it is the least clearcut as to what the sources of the emission are. The "richness effect" suggested in fact has an underlying assumption: that the star formation efficiency is approximately constant in galaxies, or more  $H_2$  would *not* make more of everything.

DOPITA: I would like to comment on two observations made by Ian Evans and myself, which may be relevant to the enhanced SFR in the vicinity of Seyfert nuclei. First, the H II regions around these nuclei all show metallicity which is considerably higher than solar. Second, in NGC 1068, Evans has found a string of knots closely mixed with the H II regions with [Ne V] emission stronger than  $H\beta$ , but which do not show the strong [O III] which might be expected for a non-thermal ionization source. We do not understand the mode of excitation in this case.