RAPID STAR FORMATION IN GALACTIC NUCLEI

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ABSTRACT

A large percentage of spiral galaxies are forming stars at a very high rate in their nuclei. There are indications that the process of star formation is modified significantly in these regions, compared with the solar neighborhood. The star formation may be fueled by interstellar material that is captured by the nucleus. Further work is needed to explore these possibilities and to establish the evolutionary connections among galactic nuclei, various types of which can be distinguished by their radically different infrared properties.

One of the big surprises from the pioneering infrared astronomy of the '60's was the large infrared excesses of a number of galactic nuclei (see, e.g., Pacholczyk and Wisniewski 1967; Kleinmann and Low 1970). Entering the '70's, three basic questions had grown out of this discovery: 1.) how prevalent are high nuclear luminosities in galaxies; 2.) what is the radiation mechanism; and 3.) how is the luminosity produced. During this past decade, we have been able to answer all three of these questions, at least in a tentative way. The answers reaffirm the suggestions already made in the 60's that infrared observations would force major reassessments in our view of galactic nuclei.

The first systematic attempt to measure the incidence of infrared excesses found that $\gtrsim$ 40% of bright, nearby spiral galaxies have strong nuclear emission at 10 μm (Rieke and Lebofsky 1978). Far infrared observations by Telesco and Harper (1980), Becklin et al. (1980), Rickard, Harvey, and Thronson (1980), and Harper (private communication) show that most of the galaxies bright at 10 μm have even larger excesses near 100 μm. The infrared emission accounts for luminosities in the range of $\sim 10^9$ to $\sim 3 \times 10^{10}$ $L_\odot$, from regions

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typically a few hundred parsecs in diameter. The high incidence of such large power outputs is a new and important input to theories of galactic evolution.

The emission mechanism for the infrared fluxes has been identified as thermal reradiation by dust (except for QSOs and some type 1 Seyfert galaxies, where the mechanism is still uncertain). This conclusion was first suggested by the general shape of the far infrared energy distribution and its resemblance to the spectra of Galactic thermal sources such as HII regions (see, e.g., Telesco and Harper 1980). A beautiful confirmation of this conclusion is the spectrum of M82 from 5 to 30 μm (Gillett et al. 1975; Willner et al. 1977; Houck, Forrest, and McCarthy 1980), which shows a wealth of absorption and emission features also detected from Galactic thermal sources. Where observations are available (e.g., Gillett et al. 1975; Lebofsky and Rieke 1979), similar features are found in the spectra of other galaxies.

The identification of the luminosity source as hot, young stars rests largely on indirect evidence. The infrared emission is extended on a scale that is difficult to reconcile with the hypothesis of a single, compact, active nuclear source (see e.g., Rieke and Low 1975; Becklin et al. 1980; Rieke et al. 1980). The sizes and other characteristics of the sources strongly suggest an analogy with the inner few hundred parsecs of our Galaxy, which is generally agreed to be an important site of star formation (Oort 1977). The far infrared spectra already mentioned, the strong silicate absorption features at 10 μm, the probable association of far infrared emission with nuclei containing dense molecular clouds detected through mm-wave CO emission (Rickard, Harvey, and Thronson 1980), and the powerful emission-line spectra of the brightest infrared-emitting nuclei (see, e.g., Beck et al. 1978; Beck et al. 1979; Simon, Simon, and Joyce 1979; Rieke et al. 1980) are all strong indicators of similarities between conditions in these galactic nuclei and those in clearly recognized regions of star formation.

Other questions are suggested by the answers obtained so far. Three which seem especially important are: 1.) how is the process of star formation affected by conditions in galactic nuclei; 2.) can the wide range of properties from one nucleus to another be related in an evolutionary sequence; and 3.) what mechanism initiates and sustains the star-forming activity.

To illustrate possibilities for studying the process of star formation in infrared-luminous galactic nuclei, I will describe and expand on a recent study of M82 (Rieke et al. 1980). Given the continuing controversy over the stellar content of a well-behaved nucleus like that of M31 (Faber and French 1980; Persson et al. 1980), it may seem surprising that much of use can be deduced about the content of M82. However, conditions in the latter galaxy are sufficiently extreme to compensate for our inability to observe some of the traditional indicators of stellar content.

With currently available observations, five basic constraints can be placed on models of the stellar population in M82. These constraints are: 1.) the bolometric luminosity; 2.) the luminosity from red giants and supergiants; 3.) the ionizing flux; 4.) the mass; and 5.) star formation and evolution should be along "plausible" lines. The luminosity can be estimated from far infrared measurements and the distance of M82. From the depths of the CO bands near 2.3 μm and the general spectral behavior to 5 μm, it appears that the flux in the K photometric band (2.2 μm) is virtually all from red giants and supergiants. To estimate the luminosity from these stars, this flux must be corrected for extinction, which can be estimated from the relative prominence of the nucleus of the galaxy at various near infrared wavelengths to be $A_V \gtrsim 20$ (Rieke et al. 1980). The ionizing flux can be determined from the Bα line strength (Willner et al. 1977; Simon, Simon, and Joyce 1979), corrected for extinction by comparing the relative Bγ strength with the predictions of case B recombination. The mass can be estimated from the rotation or velocity dispersion, although errors could arise from the heavy extinction or from non-circular motions. At present, the most reliable rotation curve is probably that in the [NeII] line at 12.8 μm (Beck et al. 1978), although estimates of the mass by other means are in close agreement. An even more convincing determination of the mass could be made by measurements of velocities in the stellar CO bands near 2.3 μm, since non-circular motions would be unlikely to affect these observations. Figure 1 shows the velocity dispersion in these bands in an 8" beam from a spectrum at 2.6 cm^{-1} resolution (M. J. Lebofsky, private communication). The spectrum itself is shown at slightly reduced resolution in Figure 2. The dispersion has been analyzed by a correlation technique similar to that discussed by Tonry and Davis (1979). The upper limit on the velocity dispersion of $\sim$ 140 km/sec places an upper limit on the mass that is within a factor of two of the estimate from the [NeII] line. Finally, "plausible" patterns of star formation and evolution can be imposed by introducing an initial mass function as close as possible to that in the solar neighborhood, letting stars be born at some appropriate rate, and then permitting the stars to evolve along theoretical-empirical tracks to provide a series of population models for comparison with the other constraints (Rieke et al. 1980).

Three main conclusions can already be drawn from this approach. The first is that rapid star formation over a period of 10^7 to 10^8 years can explain all of the characteristics of M82 except possibly for the ultra-compact radio source. The models that account for the optical-IR properties as expressed by the five basic constraints discussed above predict a supernova rate adequate to account also for the X-ray emission and, if proper account is taken of the influence of the dense interstellar medium, for the nonthermal radio emission. This success adds weight to previous arguments that rapid star formation can provide the large infrared luminosities of galactic nuclei. The second conclusion is that the required mass of recently formed stars must be comparable to the total mass of gas in the same region

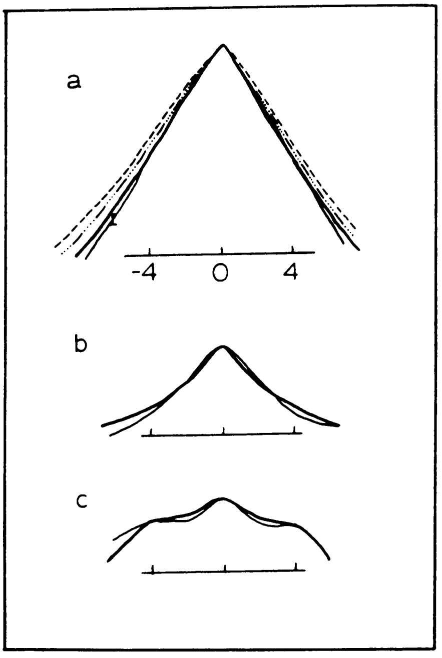

Figure 1. Velocity Dispersion for M82. Auto- and cross-correlations are plotted as a function of wavenumber (indicated in the horizontal scale under curves a) for the 2-0 CO bandhead (curves a), the 3-1 bandhead (b), and 4-2 bandhead (c). The heavy lines are the auto correlation of an artificial galaxy spectrum with zero velocity dispersion. The light, continuous lines are the cross-correlation of the spectrum of M82 with the artificial galaxy spectrum. The dashed line is the cross-correlation with the dispersion of M82 artificially broadened by 270 km/sec; the dash-dot line is the cross-correlation with an artificial broadening of 135 km/sec. A typical error bar is shown in a. All the spectra have an intrinsic resolution of 2.6 cm^{-1}, or 180 km/sec., and use a beam 8" in diameter. It can be seen that the dispersion of M82 is not detected, corresponding to an upper limit of ∿ 140 km/sec.

as estimated from the mm-wave CO observations. Thus, the star formation must be very efficient in terms of the proportion of the interstellar medium that is converted to stars. The third conclusion is that, unless all the methods of estimating rotational velocities are wrong by at least a factor of two, the relative number of solar mass stars formed must be far less than in the solar neighborhood.

This kind of study needs to be improved and expanded. For example, infrared observations can refine our estimates of the nuclear masses by

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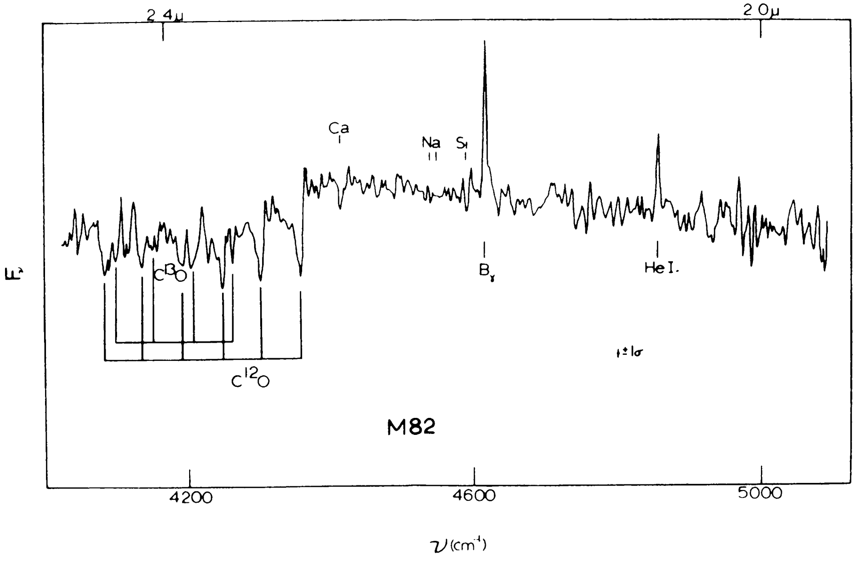

Figure 2. Spectrum of M82 near 2 μm. The beam size is 8", and the resolution is 4 cm^{-1}. The typical error bar applies to the spectral range 4250 cm^{-1} to 4800 cm^{-1}; outside this range, telluric absorptions decrease the signal-to-noise.

obtaining more detailed spectroscopy of the CO bands. New constraints on the stellar population can be obtained with high-quality infrared spectra, such as in Figure 2, combined with an adequate catalog of stellar spectra. Most importantly, these studies need to be extended to other galaxies, particularly those where the optical data are less compromised by extinction than in M82, in order to determine any biases resulting from some chance aspect of M82 itself.

The second area needing study is the evolutionary connection among different types of galaxy nuclei. Some examples are shown in Figure 3, which compares the nuclei of M31 (virtually no infrared excess), M81 (strong excess at 5, 10, and 20 μm; modest or no excess in the far infrared), M82 (typical of the nuclei whose luminosity is dominated by far infrared emission), and two Seyfert galaxies with strong thermal excesses. Many other distinctions can be made among these galaxies--e.g., M82 and NGC 1068 both contain dense interstellar clouds detected through CO emission, while such clouds are absent for M31 and M81 (Rickard, Harvey, and Thronson 1980). Comparison of the spectrum in Figure 2 with a composite spectrum of M81 and NGC 4736 shows that the stellar $C^{12}O$ absorption bands are stronger in M82 than in M81/NGC 4736. The $C^{13}O$ bands are much stronger in M82. The emission line spectrum is relatively weak in M81/NGC 4736.

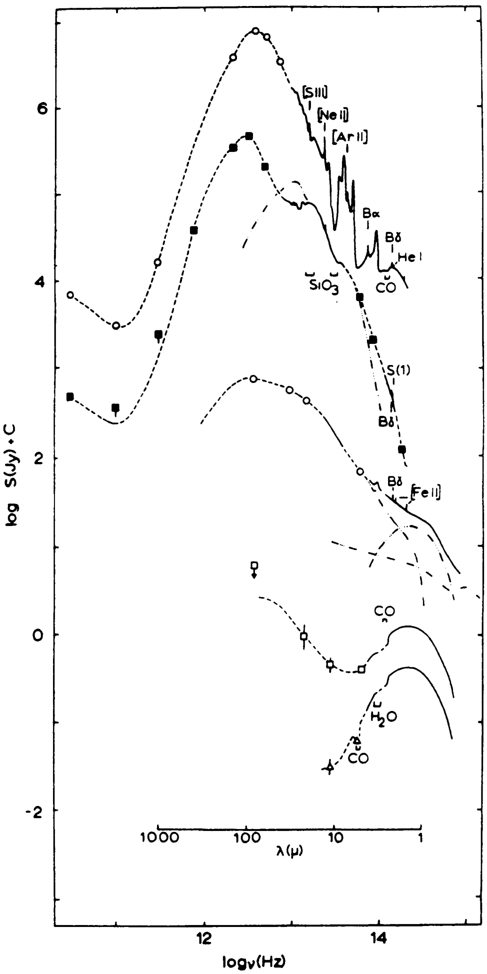

Figure 3. Spectral Energy Distribution of M82, NGC 1068, NGC 4151, M81, and M31 (reading top to bottom). The dash-dot curve for NGC 1068 represents the theoretical calculations of Jones et al. (1977): those for NGC 4151 show a possible division of its spectrum into thermal infrared, stellar, and nonthermal components. Various detected gaseous emission lines and stellar and interstellar absorption features are indicated.

Galaxies like M82 and NGC 253 have many of the attributes of type 2 Seyfert galaxies, including 1.) luminosities in the usual range; 2.) bright, compact nuclei that would appear as unresolved, and semi-stellar if the galaxies were a bit further away; 3.) radio and X-ray luminosities in the usual range; 4.) strong emission lines; and 5.) non-circular motions of ionized gas out of the galactic plane, so that the emission lines would have structure and possibly would appear broad if the galaxies were viewed face-on. Although there is no question that some Seyfert galaxies, such as NGC 4151, contain active nonthermal nuclear sources, it is likely that many type 2 Seyfert galaxies are very closely related to M82 and NGC 253, and that their nuclear activity is a result of star formation.

We have only begun to make observational distinctions based on the infrared properties of galactic nuclei. The three or four categories that can be identified now are presumably only samples of a whole continuum of properties. With more understanding of this continuum, we should be able to determine the lifetimes, frequencies of occurrence, and patterns of evolution for the episodes of rapid star formation.

Thirdly, we need to study mechanisms which could initiate and sustain the star-forming activity. For example, if the same body of gas is used for repeated episodes of star formation, we would expect enrichment of the heavy elements and isotopic anomalies (e.g., an increase in the C^{13}/C^{12} ratio) to be detectable. Most optical indications of abundance gradients in galaxies refer to an old stellar population and therefore to material that has not participated in the recent evolution of the nucleus. The present evidence from observation of fine structure lines of neon, sulphur, and argon is that the enrichment above solar-type abundances is small or non-existent (Gillett et al. 1975; Willner et al. 1977; Beck et al. 1978; Simon, Simon, and Joyce 1979). The relatively strong $C^{13}O$ absorption in the stars in the nucleus of M82 probably results at least in part from a population of luminous and cool stars. Thus, there is at present no evidence for extensive processing of the interstellar material in these galactic nuclei, although this conclusion is tentative until we improve our understanding of the extinction, stellar populations, and excitation states in these regions.

If the gas is relatively unprocessed, it may be that the star formation is fueled by material that only recently came into the nucleus. It would then be easy to understand why pairs of galaxies such as NGC 5194/5195 frequently show infrared excesses and other indications of star formation (Larson and Tinsley 1978), since tidal disturbances might inject gas into their nuclei. However, other galaxies bright in the far infrared--e.g., NGC 253, NGC 6946--are members of sparse clusters or are even isolated. The influence of the environment of the galaxy on its nuclear activity has so far not been studied systematically.

The problems I have posed here are not easy ones. However, we should be encouraged by the substantial progress during the past decade. With the sudden availability of three optimized infrared telescopes of 3 meters or larger aperture, the IRAS infrared survey, and the continuing development of infrared technology, the '80's promise exciting insights to rapid star formation in galactic nuclei.

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DISCUSSION FOLLOWING PAPER DELIVERED BY G. H. RIEKE

T. L. WILSON: Arguments about mass of interstellar gas and isotope ratios based on radio observations of ^{12}CO and ^{13}CO should be treated with care, because of the low signal-to-noise ratio, the large optical depths in CO, excitation effects, and beam-filling factors.

RIEKE: Determining the mass by the use of CO measurements is only one of four or five methods used, and probably not the strongest of those.

WYNN-WILLIAMS: It seems to me that your derived mass in M82 is subject to serious systematic underestimation. M82 is an edge-on galaxy, so the velocity profiles you use are an integral along a line of sight. All the velocities along your line of sight will tend to be less than the velocity at the tangent point, which is the velocity you must use to get your mass. How do you make allowance for this effect, especially when your prime data, the neon velocities, are of such low signal-to-noise ratio?

RIEKE: The compactness of the 2 μm map shows that we are seeing predominantly the nucleus of the galaxy, so the effect you mention is not going to affect things there. There are also compensating effects which tend to lead to an overestimation of the mass on a theoretical basis, namely the fact that we take a spherical distribution of stars. There are systematic effects in each rotation curve, but the fact that they all agree in terms of upper limits or measured masses should seriously embarrass anyone who wants to say that the masses are substantially larger than those which lead to requiring the IMF to cut off towards 1 $M_\odot$ stars. To avoid this conclusion you would need peak velocities 2-3 times larger than the largest observed velocities.

WYNN-WILLIAMS: In our Galaxy discrete supernova remnants contribute only a small portion of the extended non-thermal radio radiation. As far as I know, efforts to link the strength of the extended Galactic non-thermal radio emission to the supernova rate, let alone the star formation rate, have been unsuccessful. In view of the uncertainty in our Galaxy, how can you use this as a constraint in M82?

RIEKE: In M82 we are dealing with recent rapid star formation, so we can attribute things rather directly to what has happened, without worrying about the pre-existing population of stars. The analysis is only qualitative in terms of the effects of supernovae, but if you take the radio output of Galactic supernova remnants as a function of age and apply that to the supernova rates predicted for M82 you find quite close agreement with observation for the radio output.

WYNN-WILLIAMS: But discrete supernova remnants in our Galaxy are seen only for a few times 10^4 years, whereas your starburst models last for 10^7 years.

RIEKE: The interstellar medium in M82 is sufficiently dense, and the photon field is sufficiently dense, that the effects of the energetic electrons are negligible after a few times 10^4 years.

BECKLIN: Your model of the star formation rates in M82 depends on the strength of the 2.2 μm continuum radiation from late type stars, yet in the figures you presented, the 2.2 μm distribution looked totally different from the 10 μm distribution. Would you like to comment?

RIEKE: The stars dominating the 2 μm emission are a few time 10^7 years old if you look at these models. In that time the stars will have rotated around the nucleus 3-10 times, so will have a more relaxed, symmetric distribution than the younger objects seen at 10 μm.

RICKARD: It should be noted that sometimes 10 μm is not infrared enough to pick out molecular clouds. NGC 5195 is a stronger 10 μm source than its companion, M51, yet it is weaker in the 2.6-mm CO line by more than a factor of 20. Clearly, if you select by 10 μm emission, you can still get a rather heterogeneous set of objects.

RIEKE: This is why I emphasize the importance of 100 μm observations. There are galaxies which have strong 10-20 μm excesses, yet have either no strong 100 μm flux density or no Bγ line flux. We now have about two dozen galaxies measured at 100 μm, and I hope we'll have two dozen dozen at least by the end of the decade.

WERNER: Many of the links between star formation and high luminosity which you mentioned are rather tenuous or circumstantial. I think the best indicator is the presence of ionized gas as revealed by radio continuum or Bγ emission. What evidence is there, based on energetic or statistical grounds, that the high far infrared luminosity in these galaxies is episodic rather than continuous?

RIEKE: There is a problem of fitting things together if they are continuous, in that the conversion of mass to luminosity is so high in some of these galaxies that the mass is used up very quickly. We do not yet know whether some galaxies have recurrent episodes and others none; there is a lot of work to do in terms of the evolution between one kind of galaxy and another.

PERSSON: Could you comment on the possibility of deriving abundances of sodium and calcium in the nucleus of M82 using the 2 μm spectrum?

RIEKE: It is an intriguing possibility, but so far people have not yet succeeded in using these lines to get abundances in Galactic stars, and it is certainly more difficult to determine them in galaxies like M82. As far as comparisons between galaxies go, this is already part of our long term spectroscopy program, but the strength of the lines is affected by things like surface gravity, temperature, luminosity, which all have to be corrected for.

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PUGET: Can you say anything about the ratio of 5 GHz to far infrared flux densities as compared to Galactic complexes?

RIEKE: At 5 GHz the flux from M82 is almost completely dominated by the non-thermal component. From the Brackett lines we may deduce the radio thermal emission, and we find that, unless the H II regions are extraordinarily dense, we can account for virtually all of the measured 3-mm radio emission by free-free processes. This can be understood if Compton scattering of the energetic electrons steepens the non-thermal radio spectral index longward of 3-mm wavelength. This is not a unique model, however.

HARPER: Pertaining to your comments on the extent of the infrared sources, we have recently measured the size of NGC 1068 at 60 μm and find that it is approximately 25" in diameter. This corresponds to a linear size of about 2000 pc. Also, preliminary results on several less luminous galaxies are consistent with similar scale sizes. On the basis of these data, I expect that we will find far infrared activity and high rates of star formation extending to rather large radii in the nuclear regions of many galaxies.

RIEKE: I might add that when we talk of an evolutionary sequence of galaxies the spectral information is in some sense the most straightforward to obtain, but we may also find that there is an evolutionary sequence as regards structure and size scales. All these things need to be folded in in order to really get an understanding of how one type of galaxy relates to another.

A. S. WILSON: I think it's important to remember that not all of the properties of Type 2 Seyfert galaxies, to which you alluded, can be explained in terms of a burst of star formation. Firstly, the X-ray emission in at least 3 galaxies with Type 2 optical spectra are variable on a time scale of months. Secondly, a few Type 2's have double radio sources in their nuclei. Both of these results indicate (the first more conclusively than the second) that there is something ultracompact in these objects.

RIEKE: What I meant to suggest is that there is an overlap; and that some Type 2 Seyferts may well be manifestations of star formation, and some of them will have more active sources in their nuclei. Part of getting an evolutionary sequence in these galaxies is to sort out which are which.

BECKLIN: I think it would be a mistake not to point out that studies of the Galactic Center will be very important for understanding the phenomena in galactic nuclei discussed here. This is true because of its relatively close proximity to us. We can get better velocity and mass determinations, star formation rates, gas, dust, and star densities, and potentially a more detailed understanding of the interaction with the active source in the very center.

TOVMASSIAN: I would like to remark that all data presented here by Rieke are in excellent agreement with Ambartsumian's hypotheses on the activity of galactic nuclei and formation of stars by explosion of superdense protostellar matter.

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