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THE RELATION BETWEEN STAR FORMATION AND ACTIVE NUCLEI

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ABSTRACT

Three questions relevant to the relation between an active nucleus and surrounding star formation are discussed. The infrared stellar CO absorption bands can be used to identify galaxies with large populations of young, massive stars and thus can identify strong starbursts unambiguously, such as in NGC 6240, and can help identify composite active/starburst systems such as Arp 220. An active nucleus is probably not required for LINER spectral characteristics; dusty starburst galaxies, particularly if they are nearly edge-on, can produce LINER spectra through the shock heating of their interstellar media by supernovae combined with the obscuration of their nuclei in the optical. The Galactic Center would be an ideal laboratory for studying the interaction of starbursts and active nuclei, if both could be demonstrated to occur there. Failure to detect a cusp in the stellar distribution raises questions about the presence of an active nucleus, which should be answered by additional observations in the near future.

INTRODUCTION

The interaction between classic galaxy activity — the presence of a nonthermal source that dominates the energetics of the galaxy nucleus — and star formation in the galaxy is a topic on which there is a certain amount of speculation but relatively little relevant observation. IRAS should bring insights to this interdependence because much of the luminosity of both active nuclei and starbursts emerges in the infrared. However, obscuration by the interstellar dust associated with a starburst can hide the galactic nucleus in the visible and ultraviolet, making it necessary to develop new tools to distinguish and study these processes. This talk deals with three issues in this area: the use of stellar CO bands to identify powerful starbursts, the generation of LINER (Low Ionization Nuclear Emission Region) spectra by starbursts, and the possibility of observing the interaction of an active nucleus and a starburst in intimate detail in the Galactic Center.

USE OF CO BANDS TO IDENTIFY STARBURSTS

Traditionally, the presence of a large population of young, massive stars in a galaxy has been identified through observations in the blue or ultraviolet, such as an ultraviolet excess or the presence of Balmer lines in absorption. However, in powerful infrared starburst galaxies, the optical depths in interstellar extinction in the blue can be immense, so these indicators are inadequate. One example is the historical difficulty in identifying the type of activity in the prototype infrared starburst galaxy, M82.

Virtually all types of cool stars have CO absorption bands in their spectra between 2.3 and 2.5um, where they can be readily observed. The depth of these bands depends on the stellar luminosity and metallicity (e.g., Frogel et al. 1978; Frogel, Cohen, and Persson 1983). Luminous galaxies without recent star formation have nearly identical CO band strengths (Frogel 1985 and references therein), indicating that the the infrared outputs are dominated by stellar populations with red giants of comparable mass and metallicity from galaxy to galaxy, corresponding to a main sequence turnoff slightly above one solar mass.

A starburst adds to this quiescent stellar population an additional population of much more massive stars. As soon as these stars evolve to the red supergiant phase, they will tend to produce abnormally deep CO absorption in the galaxy spectrum. If the starburst luminosity is large enough compared with that of the pre-existing quiescent stellar population, this deepening should be detectable. In fact, such deepening has been observed in M82, NGC 253, and NGC 6240, requiring that their near infrared spectra be dominated by the young, massive stars produced in starbursts.

There is evidence for very strong reddening in all three of these galaxies. However, all of them have H - K colors that are too red compared with their J - H colors for any reasonable stellar population plus foreground reddening. For NGC 253 and NGC 6240, it has been suggested that this red color arises from a normal quiescent stellar population, plus an infrared excess at 2um contributed by a nonthermal nuclear source or by thermal reradiation by dust(Scoville et al. 1985, DePoy, Becklin, and Wynn-Williams 1986). Such an excess could only dilute the CO band strength; the observed strengths require that the 2um emission be dominated by starlight from massive stars. The red H - K colors can be explained if the interstellar dust is mixed with the stars in the galaxy, so there are optical depth effects in the source, or if the extinction varies over the extended source region. J, H, K images of the three galaxies show strong color variations, which are almost certainly due to extinction variations over the sources. These data are illustrated in Figures

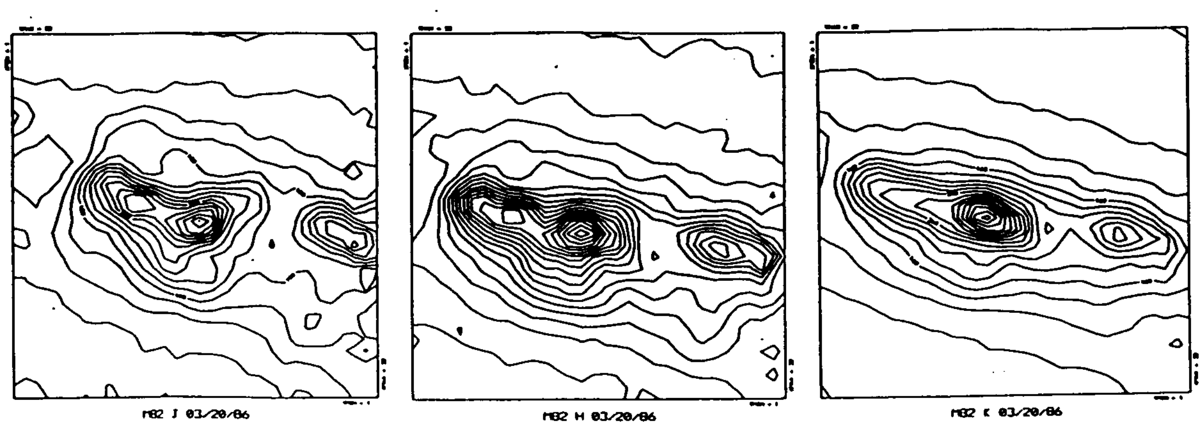

Figure 1. Images of M82 at J, H, and K (left to right). The frames are 27 arcsec on a side and the pixels are 0.85"; the data have been smoothed to a final resolution of 1.7". At K, the image shows a reasonably symmetric, smooth distribution of stars that suggests an edge-on disk around a brighter nucleus. Note the strong distortions from interstellar extinction as the wavelength becomes shorter.

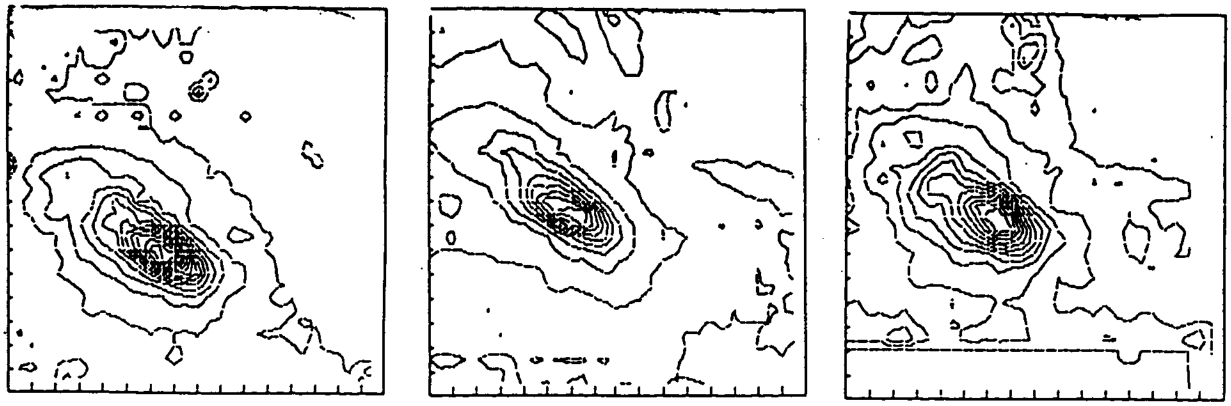

Figure 2. H and K Images of NGC 253 and Their Ratio (left to right). The frames are 27 arcsec on a side and the pixels 0.85". In the ratio K/H, there is an extended peak centered on the galaxy nucleus, indicating it is bluer than the surrounding regions.

1 - 3. At least from these examples, the strong infrared excesses typical in starburst galaxies appear to be a minor part of their emission at wavelengths as short as the 2um CO bands.

M82, NGC 253, and NGC 6240 have luminosities from red supergiants respectively of 2.5 X 10^{10} L_O (Rieke et al. 1980), 1.3 X 10^{10} L_O (Rieke et al. op. cit.) and 2 X 10^{11} L_O (Rieke et al. 1985, but with A_V set to 7, from the H - K excess), compared with far infrared luminosities of 3 X 10^{10} L_O, 3 X 10^{10} L_O, and 5 X 10^{11} L_O. Thus, the stellar luminosities deduced directly from the near infrared can account for 30 to 40% of the total infrared luminosity of the galaxy. This result arises because a coeval population of massive stars evolves in a few million years to emit a substantial fraction of its luminosity from red supergiants.

In contrast to starburst galaxies, the near infrared continua of Seyfert galaxies seem to be dominated by featureless continua; the CO bands when present are diluted substantially compared with those in galaxies with quiescent stellar populations (e.g., Cutri et al. 1981). Where relatively strong CO bands are detected along with indications of an active nucleus, the system is likely to be a composite. Arp 220 is an example; despite spectroscopic exidence for a Seyfert nucleus, its CO bands are stronger than those of quiescent galaxies (Rieke et al. 1985). Assuming A_V = 7 (corresponding to the H - K excess), a stellar luminosity of 6 X 10^{10} L_O is detected directly in the near infrared. Assuming a ratio of red giant and supergiant to total stellar luminosity similar to those in M82, NGC 253,and NGC 6240, the starburst accounts for 15 to 20% of the total luminosity of Arp 220.

LINER SPECTRA IN LATE TYPE GALAXIES

LINER spectra were originally thought to arise by shock heating, but it has recently become popular to ascribe them to the presence of a weak, powerlaw excitation spectrum produced by an active nucleus. Most of the evidence for this interpretation comes from observations of early type galaxies. However, similar spectra are observed in late type galaxies where there are many indications of starburst activity. These galaxies raise the question of whether starbursts can produce a LINER spectrum.

We have considered this question in detail for NGC 253 (Rieke, Lebofsky, and Walker 1986). The high supernova rate in the nucleus of this galaxy repeatedly shocks the low density interstelar medium with supernova blast waves that produce the starburst wind seen in the x-ray (Fabbiano and Trinchieri 1984) and discussed by Chevalier and Clegg (1985). The molecular clouds in the nucleus are immersed in this medium, while extranuclear clouds surround it. The nuclear starburst region is heavily obscured by these clouds -- in the case of NGC 253, there is an average A_V of about 12. The radius of the Stromgren sphere for the nucleus does not extend beyond the region of heavy obscuration except where the interstellar medium is of low density. However, the low density ISM is dominated by supernova driven shocks. Thus, optical spectra do not probe the region of HII type excitation; they reflect conditions in a part of the ISM where a LINER spectrum might be expected. Heckman (this conference) reports that the filaments out of the plane of M82 also have a LINER-like spectrum, as would be expected from these arguments.

Because the extinction will tend to be concentrated in the galactic plane, a situation similar to that in NGC 253 could be expected to hold in other nearly edge on, late type, starburst galaxies with LINER spectra, such as NGC 660 and NGC 3079. In face-on galaxies, a LINER specrum can still result whenever the HII region lies behind heavy obscuration. NGC 6240 is probably a good example; from the H - K color, the strong CO bands, and the extremely red color of the dominant nuclear component in Figure 3, most of its red supergiant population and presumably much of the other starburst activity lie behind extinction of approximately A_V = 7.

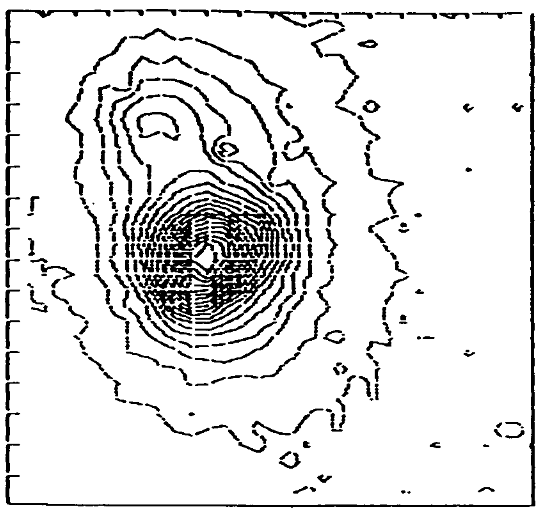

Figure 3. Image of NGC 6240 at H. The frame is 8 arcsec on a side and the pixels are 0.25". Comparison with the I image published by Fried and Schulz (1983) shows that the southern nuclear component is much redder in I - H than the northern one.

THE GALACTIC CENTER

The Galactic Center could be an ideal place to observe the interaction between an active nucleus and a starburst. Unfortunately, the presence there of either a starburst or an active nucleus has been extremely controversial. The strongest evidence for a starburst is the spectroscopic and photometric classification of a number of stars within 40 arcsec (2 parsecs) of the Galactic Center as red supergiants (Lebofsky, Rieke, and Tokunaga 1982). We have made images at H and K of 24 square arcmin centered on this region and find many additional bright red stars that are likely to be red supergiants, although spectroscopic confirmation is not yet available (Lebofsky 1986).

The evidence for a black hole (and hence an active nucleus, even if a dormant one) rests largely on the velocities of the NeII clouds (Serabyn and Lacy 1985). Given the short lifetimes of the low density gas clouds seen in neon emission, it is not certain that their motions are in equilibrium with the gravitational field; confirming evidence for the black hole is therefore desirable.

The cusp in the stellar distribution reported by Allen, Hyland, and Jones (1983) would tend to support arguments from the velocity field for the presence of a black hole. However, the image of the much larger field mentioned above confirms the presence of large nonuniformities in the extinction in this region, as suggested previously by Rieke, Telesco, and Harper (1978), and Lebofsky (1979). The central parsec of the galaxy happens to lie in a minimum of the extinction and furthermore has a number of 2um sources that are not part of the general red giant and supergiant population (Rieke and Lebofsky 1986). These two circumstances can lead to an artificial appearance of a cusp. Moreover, Allen and Sanders (1986) suggest that the compact radio source does not coincide with any sufficiently bright near infrared source to be identified with the core of a stellar cusp. However, this argument depends very strongly on the precise location of the compact radio source relative to the infrared maps. Various determinations of this location are plotted on a new, high resolution image of source 16 in Figure 4; the possibility still remains that the source coincides with a faint peak in the infrared emission.

An alternate way to look for a cusp is to measure the surface brightness between the bright stars. Assuming a central density of about 4×10^5 stars pc^{-3} (Bailey, 1980), there should be about 4000 stars per square arcsec. Most of these stars will contribute a diffuse, unresolvable background which should be an extremely accurate reflection of the distribution of stellar mass in the region. Searches for a cusp in this diffuse component will also be insensitive to the precise registration of the infrared maps relative to the position of the radio compact source.

By chance, there is a "valley" in the source distribution that comes within about 2 arcsec of the compact radio source (see Figure 4). The minimum in this valley has been compared with the minima on 32 X 32 camera frames centered on the compact source but with different pixel scales -- 0.25" (Fig. 4), 0.85", and 1.3". The lowest surface brightness on these frames lies in a small region of very high extinction first noted by Lebofsky (1979) about 20" west of the central source complex. If this region is set to zero and the bottom of the valley set to 100%, most of the remaining region between bright

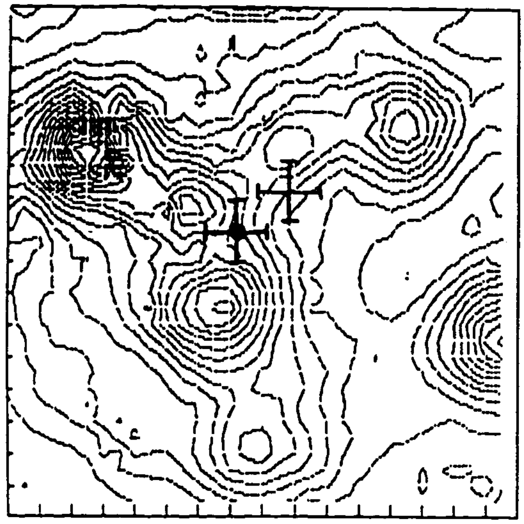

Figure 4. Image of Source 16 in the Galactic Center at K. The frame is 8 arcsec on a side and the pixels are 0.25". The cross with a dot is the location of the compact radio source according to Henry, DePoy, and Becklin (1984), while that without a dot is according to Forrest, Pipher, and Stein (1986). The "valley" referred to in the text extends from the middle of the western edge of the frame toward the southeast, ending about 2 arcsec west of the compact radio source.

sources is at a surface brightness of 50 to 75% (see Figure 5). Because the valley appears to be affected by source crowding, the true diffuse brightness there may be have been overestimated; it is also likely that the surface brightness in the zero reference region is actually larger than zero. Both of these effects will tend to reduce the true contrast between the valley floor and the surrounding regions compared with our estimate. Thus, there is an upper limit of about 1.5 to the increase in surface brightness between a distance of 1 pc and one of 0.1 pc from the compact radio source.

The apparent absence of a strong cusp in the stellar distribution leaves the question of "activity" in the Galactic Center open, but an answer should be possible soon. An improved understanding of the stellar distribution will be possible as soon as the extinction has been mapped; infrared camera images such as those described here and by Lebofsky (1986) should be capable of doing so, although the large region of extremely high extinction to the east will require images of signficantly greater sensitivity than are now available. The velocity field can be measured from spectral features in individual stars. In the 24 square arcmin field already imaged but outside the central 40 arcsec, there are 81 stars brighter than K = 9.5. Improvements in near infrared spectroscopy should soon allow velocity measurements for these stars and remove the uncertainties in the velocity field that arise because of the short lifetimes of the gas clouds measured in Ne II.

Since the Galactic Center is 1000 times closer than any classical active galaxy, even the presence of a very weak active nucleus there would help immensely in determining the interaction of such an object with the immediately surrounding galaxy.

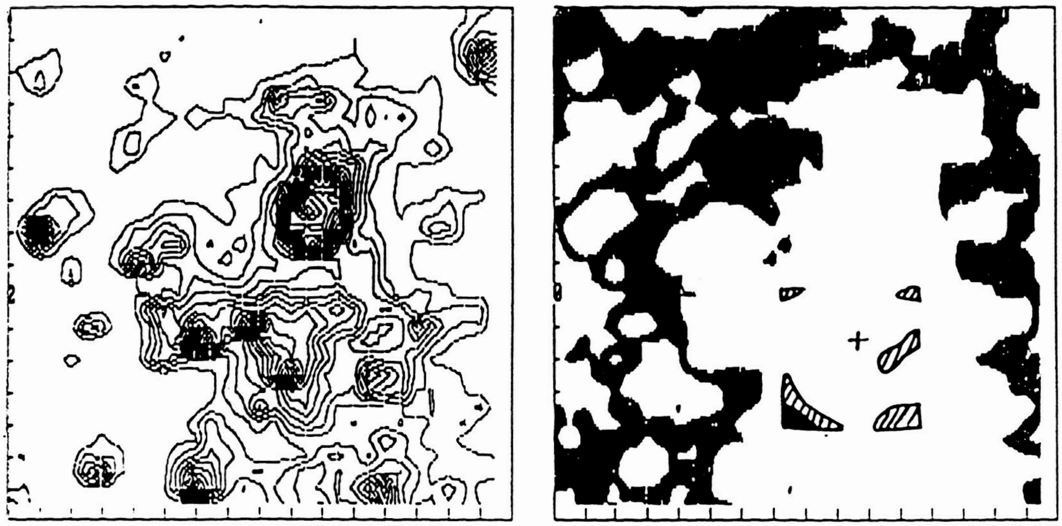

Figure 5. Image of the Galactic Center at K. The frames are 27 arcsec on a side and the pixels are 0.85". The left frame shows the sources in this region; the brightest just to the northwest of the center is source 7. In the right frame, the diffuse background between the sources is displayed, with the source 16 frame (Fig. 4) superposed. Regions where the diffuse background is 75 to 100% the surface brightness in the valley in Fig. 4 are indicated hatched. Regions where the surface brightness is 50 to 75% that in the valley are shown solid.

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QUESTIONS

T. J. Jones: One of the reasons not everbody has picked up on the interpretation of the 2um sources near the galactic center as M supergiants is because not everyone believes they are true supergiants. I believe they are mostly upper AGB stars (M_{bol} = -6 to -7) with main sequence progenitors from 3 - 7 M_o.

Answer: The spectra show a range of spectral types. Source 7, Kobayashi 9, and probably source 12 appear to be very luminous and massive supergiants and are inconsistent with your interpretation. The other stars with spectra are of lower mass and could have 3 to 7 M_o progenitors. However, all of the brighter objects appear to be massive enough that their progenitors must be relatively young ($\leq$ 3 X 10^8 years), indicating that the 2um sources formed in an extended period of recent star formation.

M. Shull: Your limits on a possible black hole in the Galactic Center depend on an equilibrium stellar cusp. If the stellar density is not sufficient, the stellar relaxation time is too long for this cusp to be established, so you might still be able to have a massive compact object.

Answer: It seems likely that the two-body relaxation time for the galactic center is too long for a fully developed cusp (i.e., stellar density as radius to the -1.75). Nonetheless, a slightly more shallow cusp would be expected (P. J. Young 1977, Ap.J., **217**,287).

J. Frogel: 1.) Galactic star clusters of near solar metallicity are all extremely star poor so that the brightest giants you can see in them are about 2 magnitudes fainter than the brightest stars you would expect to see in a large population; 2.) In Baade's window at b = -3.9^o there are M6-9 giants as bright as K = +6. These have M_{bol} of about -4.5 and, in a super metal rich environment, can still have an age of 10^{10} years.

Answer: Stars like the brightest in Baade's window will account for the fainter objects in the Galactic Center images. Taking an extinction of A_V = 30, they will have an apparent magnitude of K $\geq$ 9.4; since the extinction for most of the Galactic Center region is higher, over most of the area they will be even fainter. Six of the seven stars with spectra have K $\leq$ 8.1, and three of these six are of spectral types M1 to M4, where the Baade's window stars are fainter still.

Frogel: Stars with age a few Gyr can have very strong CO indices. These are AGB stars with M_{bol} on the order of -6. Such stars are found in large numbers in the Magellanic Clouds. Although in the Magellanic Clouds many of these are C stars, in a more nearly solar metallicity environment they would be M stars.

Answer: I don't believe the existence of these stars affects the arguments that the strong CO bands arise from a difference in stellar population that is most plausibly connected with a recent powerful episode of star formation. In determining the CO band strengths, comparison is made to galaxies with similar luminosities and metallicities, so some other difference must exist in the stellar populations.

P. G. Mezger: There is an HII region, Sgr A West, surrounding IRS 16. What, in your opinion, provides the ionization for this HII region?

Answer: The ultraviolet flux from the hot stars that should accompany the red supergiants appears to be adequate to ionize all the gas in this region. Some more exotic ionizing source may also contribute, but if such an object accounts for all the luminosity of the region, it is surprising how difficult it is proving to be to establish its existence for sure.

E. E. Becklin: Is it not a problem to assume a normal IMF in a region like the Galactic Center - especially the very central region?

Answer: Of course, the process of star formation should be modified by conditions in these regions. There is evidence, for example, that low mass stars form in much lower relative numbers in starbursts than in the solar neighborhood. One would expect that the modifications would get larger as one approached the nucleus; yet, in NGC 253 most of the starburst appears to lie within 20 parsecs of the nucleus, so there is no evidence for a cutoff in the process of massive star formation.

M. Harwit: Have you looked at the time scale over which a dust shroud surrounding a concentrated, higly luminous (10^{11} L_{o}) group of stars would become disrupted by the strong radiation pressure which should dominate gravitational attraction?

Answer: No. I suppose it would depend on some parameters that we don't have good estimates of, such as the magnetic field. Perhaps with more work on the timescales for the starbursts in NGC 6240 and similar galaxies, we could make some progress in this area.