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STRUCTURE IN THE NUCLEUS OF NGC 1068 AT 10 MICRONS

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New 8 - 13 μm array camera images of the central kiloparsec of Seyfert 2 galaxy NGC 1068 resolve infrared source structure which is extended and asymmetric (2.1 x 0.7 arcsec FWHM), with its long axis oriented at position angle 33°. Infrared emission 1-2 arcsec to the northeast of the very center of the galaxy appears coincident with a weak, barely resolved, discrete source in the kiloparsec-scale jet detected in published radio continuum maps of the galaxy.

Very Large Array (VLA) observations show a linear, clumpy structure some 10-15 arcsec (~ 1 kpc) long, extending to the NE and SW of the nucleus. This feature is usually described as a jet (Wilson and Ulvestad 1982, 1983; Pedlar et al. 1983) though at sub-arcsec resolution the emission nearest the center of the galaxy is asymmetric in position angle (van der Hulst, Hummel, and Dickey 1982; Wilson and Ulvestad 1983). Condon et al. (1982) reject the jet hypothesis altogether, arguing instead that the radio emission arises from supernovae in regions of intense star formation.

There is clear evidence of star formation in the disk of NGC 1068. The infrared (IR) spectrum of NGC 1068 resembles thermal IR spectra seen in galactic HII regions and molecular clouds. About 98% of the galaxy's bolometric luminosity is emitted between 1.5 μm and 3 mm (Rieke and Low 1975; Telesco, Harper, and Loewenstein 1976; Hildebrand et al. 1977; Telesco and Harper 1980). A 10 μm map and far-IR aperture photometry (Telesco et al. 1984) show that about 10% of the flux density at $\lambda < 20$ μm, and virtually all of the longer wavelength IR radiation, arises principally from the galactic disk at $3 < r < 18$ arcsec, in a region where CO emission also has been detected (Rickard et al. 1977; Scoville, Young, and Lucy 1983).

The infrared images of NGC 1068 (Figure 1) were used to derive maps of the spatial distribution of 8 - 13 μm color temperature (Figure 2) and warm dust opacity (Figure 3). The results suggest that there exist two point-like luminosity sources in the central region of NGC 1068, with the brighter source at the nucleus and the fainter one some 100 parsecs to the northeast. This geometry strengthens the possibility that the 10 μm emission observed from grains in the nucleus is powered by a non-thermal source. In the context of earlier visible and radio studies, these results considerably strengthen the case for jet-induced star formation in NGC 1068.

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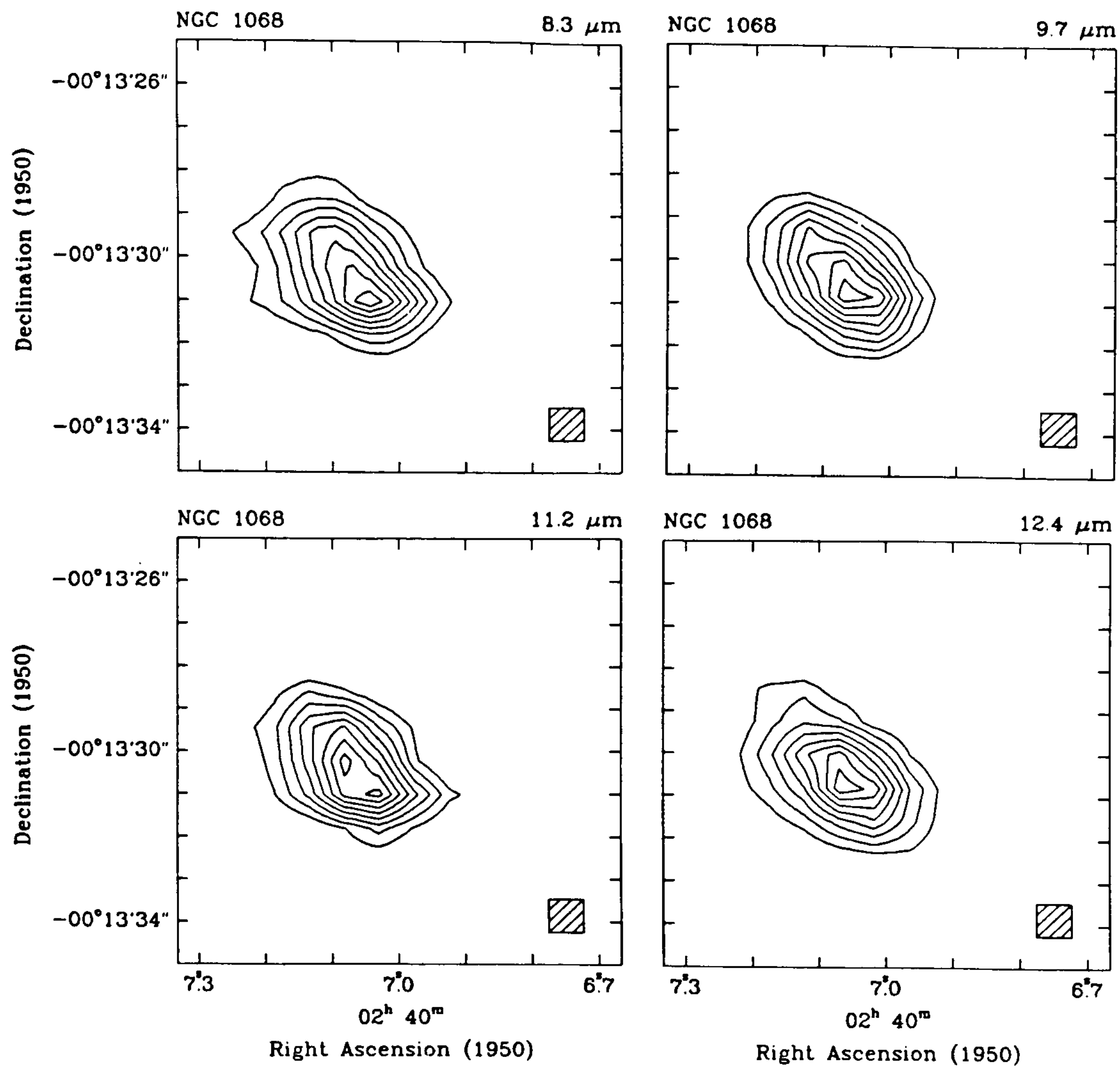

Figure 1—Calibrated isophotes for the array camera images of NGC 1068. In each case, the lowest contour level is 3σ above the mean background intensity in the periphery of the field of view, which has been subtracted from the map. The hatched square represents one 0.78 × 0.78 arcsec IR CID pixel. The contour level spacing is 1.5σ at all wavelengths: 8.3 μm (upper left), 9.8×10^9 Jy ster^{-1}; 9.7 μm (upper right), 9.1×10^9 Jy ster^{-1}; 11.2 μm (lower left), 1.3×10^{10} Jy ster^{-1}; and 12.4 μm (lower right), 1.6×10^{10} Jy ster^{-1}.

The imaging observations of NGC 1068 were made at the Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii, on 1983 August 16 using the Goddard infrared array camera system, which is based on a 16 x 16 pixel Si:Bi charge injection device (CID) array (Lamb et al. 1984; Gezari et al. 1985; Tresch-Fienberg 1985). The images were obtained in four bandpasses, with effective wavelengths of 8.3, 9.7, 11.2, and 12.4 μm and bandwidths of about 10% (Figure 1). The field of view of the array for these observations was 12.5 x 12.5 arcsec, corresponding to approximately 0.9 x 0.9 kpc.

Atmospheric conditions during the observations were very favorable; visual seeing was better than 1 arcsec. At the IRTF, the optical plate scale at the detector is 0.78 arcsec/pixel, and the diffraction-limited FWHM instrumental profile of a point source ranges from 0.9 to 1.1 arcsec between 8.3 and 12.4 μm (compared with λ/D = 0.7 arcsec at 10 μm). The actual spatial resolution of the camera system, determined from the size (FWHM) of point source calibration images, was 2.3 arcsec in R.A. and 1.3 arcsec in Dec. at all wavelengths.

The presence of a distinct IR source NE of the nucleus was tested by subtracting an instrumental point spread function (obtained from images of the reference star β Peg, c.f. Figure 5) from the array camera images and examining the remaining emission. This is appropriate because the galaxy is known to contain a compact source at its very center, based on speckle interferometry (Meaburn et al. 1982, McCarthy et al. 1982) and radio mapping (van der Hulst, Hummel, and Dickey 1982; Wilson and Ulvestad 1983).

All the images of NGC 1068 show substantial residual emission following the subtraction of a point source from the nucleus. This emission is concentrated in a small region 1.7 $\pm$ 0.4 arcsec to the NE of the nucleus at position angle 39° $\pm$ 3°. Within the uncertainties of measurement, this region coincides with the apparent extranuclear color temperature peak; it appears to be the IR counterpart of the weak radio feature described above. This new IR source emits 35% $\pm$ 10% of the total 10 μm flux density within the central 7 arcsec of the galaxy, or 7.3 $\pm$ 2.1 Jy. This demonstrates that a substantial fraction of the 10 μm emission from the central region of NGC 1068 is associated wih the radio jet outside the galaxy's core.

Close inspection of the 6 cm maps of Condon et al. (1982) and Wilson and Ulvestad (1983), as well as the 18 cm map of Pedlar et al. (1983), reveals a weak but clearly present peak in the radio continuum jet, 1.4 $\pm$ 0.2 arcsec NE of the nucleus at position angle 41° $\pm$ 9°. The 10 μm emission NE of the nucleus extends to the position of this faint radio peak, and the new color temperature and dust density maps described above indicate that there is a luminosity source there.

The existence of the NE source may be further confirmed by comparing the 8 - 13 μm appearance of the nuclear region of NGC 1068 with a simple model. Figure 4 shows a contour diagram of an IR array camera image that could result at the IRTF when observing two point sources separated by 1.6 arcsec at a position angle of 35°, with the NE source 54% as luminous as the primary source. Comparison of the real and synthetic galaxy images shows that the 10 μm morphology is reproduced quite well by this model.

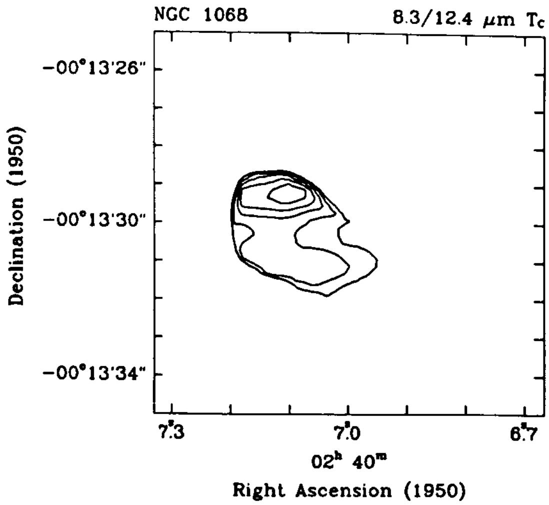

Figure 2—Map of the mid-IR color temperature near the nucleus of NGC 1068, derived from the 8.3 and 12.4 μm array camera images. Contours are plotted at 25K intervals between 300 and 425K, with the peak temperature in the NE of the map.

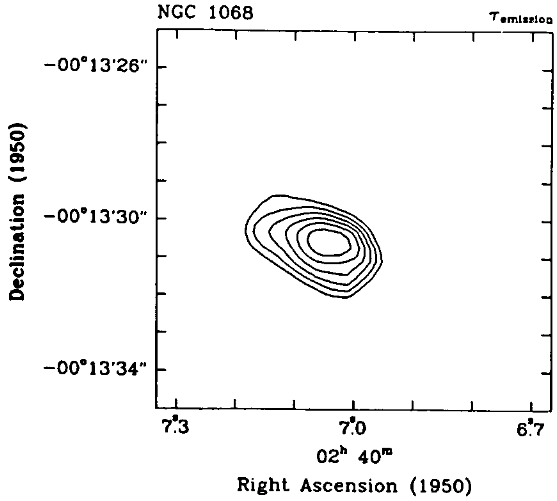

Figure 3—Map of the emission optical depth (and, by inference, the relative dust density) near the nucleus of NGC 1068, derived from the 8.3 μm intensity map and the color temperature map. Contours are plotted from $\tau = 6.66 \times 10^{-5}$ to 2.33×10^{-4}, with a level spacing of 3.33×10^{-5}.

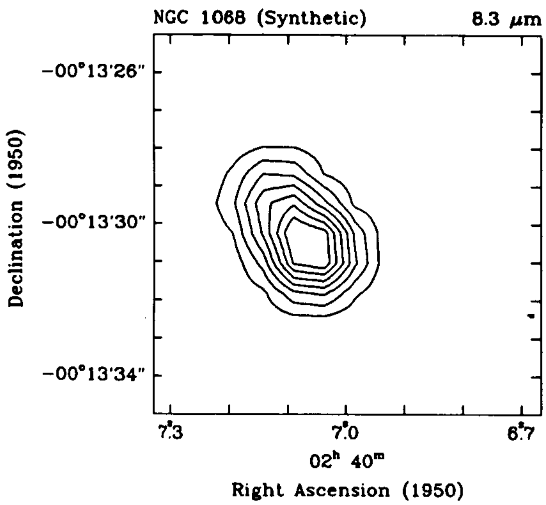

Figure 4—Contour diagram of a synthetic image generated by computing the IR array camera's response on the IRTF to a source comprised of two point-like objects separated by 1.6 arcsec at a position angle of 35°, with the NE source 54% as luminous as the primary source and spatial resolution at 10 μm of about 1.8 arcsec (the average of the 2.3 and 1.3 arcsec resolutions in R.A. and Dec. actually achieved during the observations of NGC 1068 in August 1983). The position of the primary source on the array corresponds to the assumed position of the galaxy's nucleus in the 8.3 μm array camera map (Figure 2).

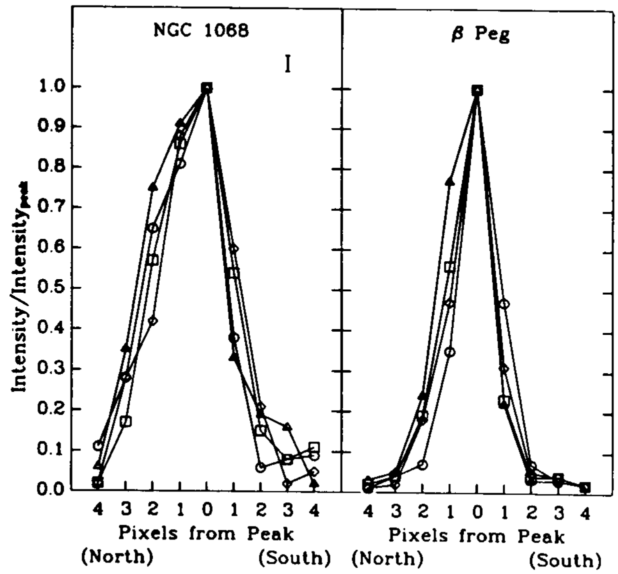

Figure 5—Intensity profiles of NGC 1068 (left) and β Peg (right) at 8.3 μm (circles), 9.7 μm (squares), 11.2 μm (triangles), and 12.4 μm (diamonds). These were generated using a 1 × 5 pixel (0.78 × 3.9 arcsec) "slit" as described in the text to simulate the declination slit scans of Becklin *et al.* (1973). All scans have been normalized to 1.0 at the peak. A sample error bar (representing only the statistical measuring uncertainty) is shown for NGC 1068; the uncertainties for β Peg are smaller than the plotted symbols.

The principal conclusions of this work are:

1. Direct images reveal an asymmetric IR source consisting of a bright peak plus extended emission several arcsec toward the NE at position angle 33°. If the IR peak is assumed coincident with the visible/radio nucleus, then the 10 μm morphology may be interpreted as a superposition of at least two sources - one at the very center of the galaxy and another some 1.5 arcsec to the NE in the radio jet, coincident wih a weak radio continuum peak.

2. Maps of 8.3/12.4 μm color temperature and IR emission optical depth (i.e., dust density) suggest that at least two sources of luminosity are required in the central few hundred parsecs of the galaxy. The new data are consistent with the 8 - 13 μm radiation arising from thermal emission by dust grains, but a compact, non-thermal source may be responsible for some of the grain heating.

3. These results suggest that the extra-nuclear radio/IR source could be a region in which star formation has been triggered by the ejection of matter in a jet from the Seyfert nucleus.

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