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100 AND 160 MICRON MAPS OF THE DUST REEMISSION FROM THE NUCLEUS AND INNER-ARM REGIONS OF NGC 6946

G. ENGARGIOLA AND D.A. HARPER
Yerkes Observatory

D.T. JAFFE
Department of Astronomy, University of Texas at Austin

ABSTRACT

Dust reemission from the Scd galaxy NGC 6946 has been measured at 100 and 160 μm with the 32-channel University of Chicago Far-Infrared Camera. We present fully sampled maps of the nucleus and inner spiral arms at 45" resolution. The far-infrared morphology of the galaxy is a bright peak centered on a diffuse disk, where the peak occurs about 24" NE of the Dressel and Condon optical center. The 100/160 μm color temperature is correlated with the Hα surface brightness. Assuming the distance from earth to the galaxy is 10.1 Mpc, we determine that Tc is 32°K at the nucleus and at radius 5.4 kpc, where there is a concentration of HII regions. In the intermediate annulus of relatively low Hα surface brightness, the temperature drops to a local minimum of 25°K at radius 3 kpc. The ratio of reradiated to transmitted stellar luminosity is ~3.0 at the nucleus and ~0.9 for the disk. The optical depth at 100μm increases from .0005 at the edges of our map to .0035 at the FIR peak. Combining our observations with a fully sampled map of similar spatial extent in CO(1->0), we determine that the ratio F_{IR}/I_{CO} at the center of the galaxy is almost twice that for the disk, where the value is more or less constant.

I. INTRODUCTION

NGC 6946 is a nearly, face-on Scd type galaxy having an especially prominent northern spiral arm (Arp 1966) and a bright, compact, starburst nucleus (Telesco and Harper 1980). This galaxy has been studied extensively from X-ray to radio wavelengths. The blue and I-band fluxes have been measured by Ables (1971) and Elmgreen and Elmgreen (1984). DeGioia-Eastwood et al. (1984) have made a determination of the massive star formation rate based on measurements of Hα, but the the most detailed study of the ionized gas morphology to date has been prepared by Bonnarel (1986). All optical measurements of the galaxy reveal that surface brightness tapers off exponentially from the nucleus. The nonthermal radio continuum (van der Kuit, Allen, and Rots 1977; Klein et al 1982) and the CO (Young and Scoville) have smooth emission profiles similar to the optical disk, but the distribution of thermal radio emission is clumpy: concentrations coincide with the nucleus and a circumnuclear ring of prominent HII regions. X-rays occur throughout the optical disk but peak at the starburst nucleus and in the vicinity of the bright northern arm (Fabbiano and Trinchieri, 1987). X-ray intensity declines more steeply with radius than the optical surface brightness, possibly because of a relative excess of X-rays from a gaseous component associated with star-forming regions in the active nucleus. The global far-infrared emission properties at λ ≤ 100μm have been determined from IRAS observations by Rice

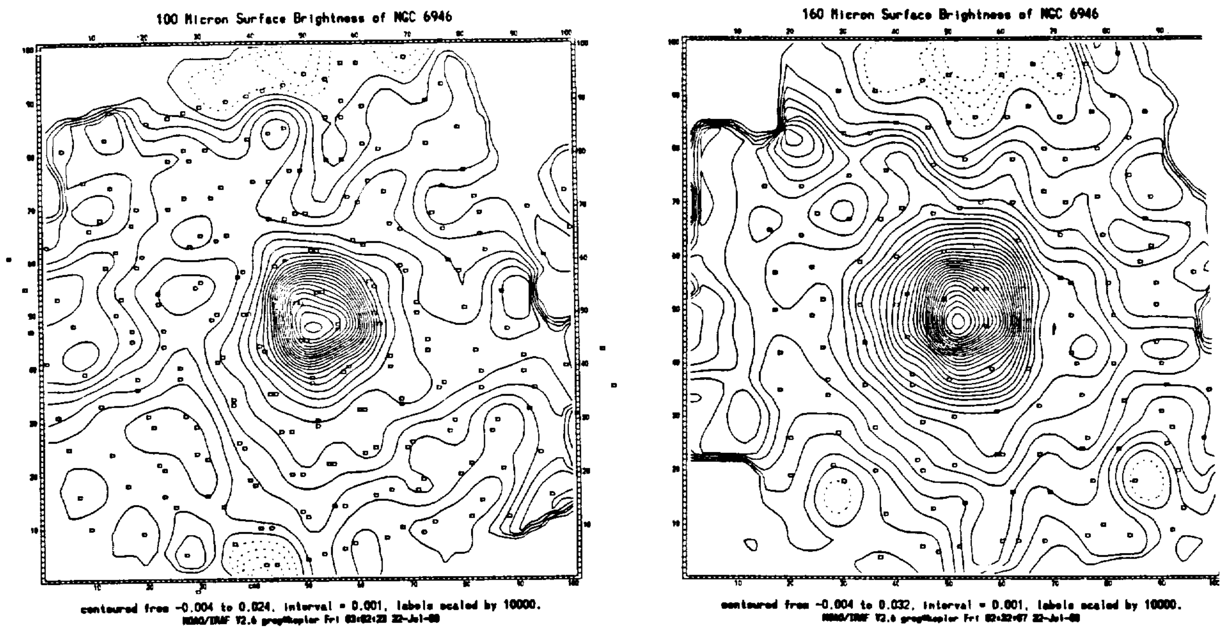

Fig. 1.- Contour maps of NGC 6946 at 100 and 160 microns. The resolution of both maps is ~45". The contours are linear and in signal units (volts).

et al. (1987). The ratio of far-infrared to blue luminosity is ~.9 indicating that half the starlight of the galaxy is reradiated by dust. The infrared and blue diameter are the same (~13'), hence the entire optical disk is obscured by quantities of dust. IRAS scans at 12, 25 and, to some extent, at 60 microns show the far-infrared emission peaks strongly on a disk of diffuse emission. Hence, the morphology of NGC 6946 is similar at all wavelengths, but with some interesting differences. In addition to an exponential disk, there is an excess of far-infrared and x-ray emission at the nucleus. Also, the distribution of HI integrated intensity has a hole 16 kpc in diameter centered at the nucleus (Tacconi and Young), beyond which the intensity rises steeply but then declines exponentially with a scalelength of 14.5 kpc. This falls outside the 4-6 kpc range of scalelengths for other surface brightness profiles.

The starlight continuum of NGC 6946 peaks strongly in the near infrared at ~1 micron and in the far-infrared at ~120 microns. In addition, there is a small peak which occurs at ~10 microns. The near-infrared peak is stellar light; the far-infrared peak is thermal reradiation of stellar photons absorbed by interstellar dust, while the mid-infrared peak is believed to be emission from small grains heated to high temperatures by absorption of UV photons from hot stars. In general, the functional form F_ν=constant x $\nu B_\nu(T_c)$ can be fit to the far-infrared peak. Tc may be regarded as a representative, but not the actual, temperature of the interstellar dust. If measurements of the galaxy are made at two wavelengths on the Rayleigh-Jeans side of spectrum, a color temperature for the dust can be computed which depends linearly on the ratio of the two measurements. However, the dependence of the emissivity on wavelength is required: for this paper, we shall assume the dependence is inverse linear.

Array detector systems developed at the University of Chicago have been used to map extensive, large scale morphology of nearby face-on galaxies such as M 51 (Smith et al.,1984) and NGC 6946 (Smith, Harper, and Loewenstein, 1984). More completely sampled maps of the inner disk and nucleus of NGC 6946 made at 100 and 160 microns are presented in this paper. For the

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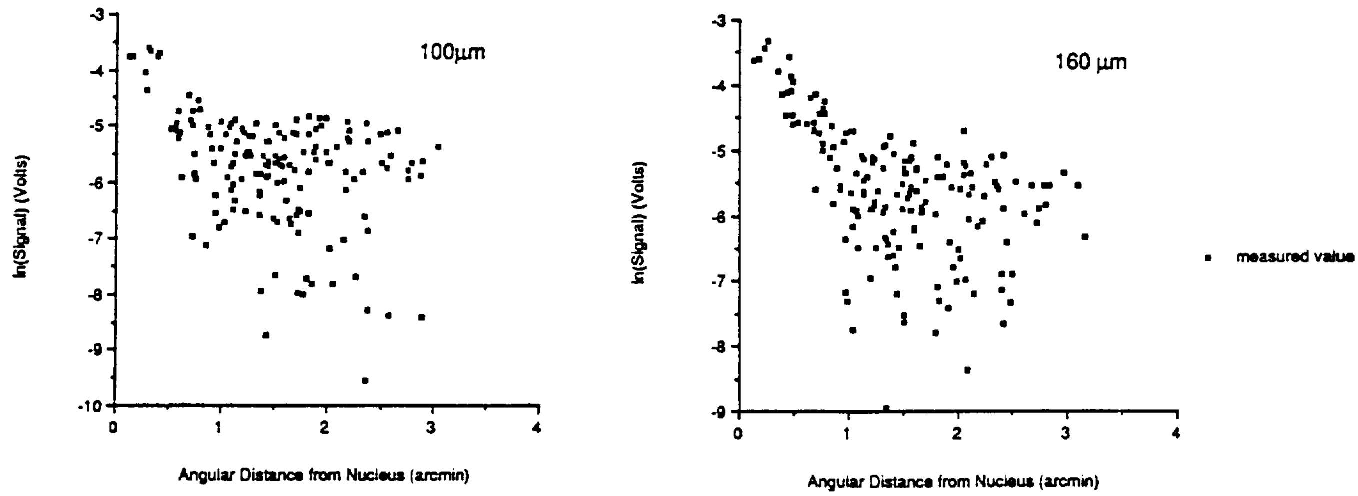

Fig. 2.- Radial distribution of the 100μm and 160μm surface brightness of NGC 6946. The logarithm of the signal measured with the camera is plotted versus the angular distance from the nucleus.

discussion, we adopt 10.1 Mpc (Rogstad, Shostak, and Rots, 1975) for the distance to NGC 6946. At this distance, our beamwidth projects to 2.9 kpc. We shall examine the dust reradiation morphology of NGC 6946 in greater detail than previous studies. Moreover, we shall study the variation of 100 micron optical depth and 100/160 micron color temperature over the galaxy, and consider the relation of these quantities to other characteristics of the interstellar medium.

II. OBSERVATIONS AND DATA ANALYSIS

NGC 6946 was mapped at 100 and 160 microns with the 32-channel University of Chicago Far-Infrared Camera mounted on the .91 m telescope of the NASA-Kuiper Airborne Observatory. The observations were made in June 1986. A brief description of the instrument and calibration procedures can be found in Engargiola et al. (1988). The detector array consists of a closed packed array of bolometer detectors having 45" beams (FWHM) and 48" center to center spacings. The boresite for the camera was found by observing M 82. Thermal background was removed by chopping the secondary mirror 4.5' off the source. W51 was the calibrator and all measured signals were corrected for atmospheric extinction due to water vapor. We estimate that the far-infrared positions are good to 5".

The galaxy was mapped by stepping the detector array through a configuration of eight points described by the corner points of two overlapping 22."5 x 22."5 squares offset diagonally from each other by about a quarter beam diameter. Such eight-point maps are oversampled. The integration time at each point was two minutes, and a single eight point map was made at each broad-band filter setting. The effective wavelengths were 100 and 160 microns. Since the sky rotates relative to the focal plane, the data points when mapped onto the celestial sphere are irregularly spaced. Using a gaussian weighting function with σ = 12."6, these points were interpolated to a regular 100x100 grid. The final maps have a resolution of ~47".

III. RESULTS

Contour maps of the 100 and 160μm surface brightness made with 45" resolution are shown in figure 1. The maps are in signal units (volts). The peak is 76Jy/beam at 100μm and 66Jy/beam at 160μm, where the beam area of each detector element is .8 square arcminutes and the dimensions of the IRAF viewport are 6'x6'. The images are oriented sky right (north-up, east-left) and are centered at (α,δ)=(20: 33: 50.4, +59: 59: 11), the far-infrared peak. When compared to a Hα map with the same resolution (figure 3), it seems clear that emission from four spiral arms has been detected at 100μm. Unfortunately, the 160μm map is not sampled as far to the east of the nucleus, and some of the spiral structure observed at 100μm has been missed. Small open boxes mark points where the surface brightness has been measured. The distribution of signals measured by the far-infrared camera versus the angular distance from the nucleus are shown in figure 2. The linear dispersion out to 1' is evidence of the oblong shape of the bright infrared peak. The distribution past 1' appears to bifurcate, where one branch is an apparent continuation of the steeply decreasing nuclear flux and the other is the true disk of the galaxy, which is fragmented into spiral arms.

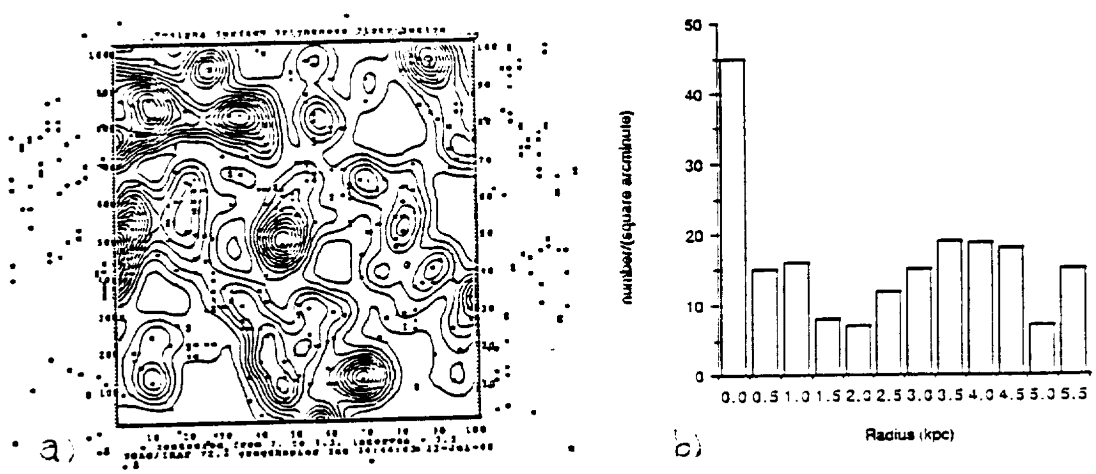

Fig. 3.- a) A linear contour map of the Hα surface brightness distribution. Light from two compact HII regions, one in the nucleus and one to the SW have been excluded. Together, they are less than 10% of the total emission, but would have dominated the extended features of the contour map. b) The radial number distribution of HII regions in the galaxy. Data from Bonnarel et al. (1986).

From the energy distribution for the central 45" of the galaxy (figure 4), it can be inferred that nearly 3/4 of the stellar luminosity from this region is absorbed by dust. The 100 and 160 μm points are from our maps; the optical and near infrared points are from Lebofsky and Rieke (1979); and, the 12, 25 and 60 μm points are obtained from IRAS maps (Rice et al.,1987) by integrating down to the 20% contour and scaling the fluxes to our beamsize of 45". The hot and cold dust components which peak at ~10 and ~100μm can be fit by the sum of a 200 and 32°K modified blackbody, respectively. Integrating under the far-infrared peaks gives $\cong 3\times10^{-12}\ \mathrm{W\,m^{-2}}$, which corresponds to a luminosity of $9.6 \times 10^{+9}$ $L_{\odot}$. The distribution of starlight transmitted by NGC 6946, which peaks at 1μm, is ≅ 1.0×10^{-12} $W m^{-2}$. Hence, the ratio of transmitted to reradiated energy from the central 45" is ~3. When calculated for the disk, this ratio is ~0.9.

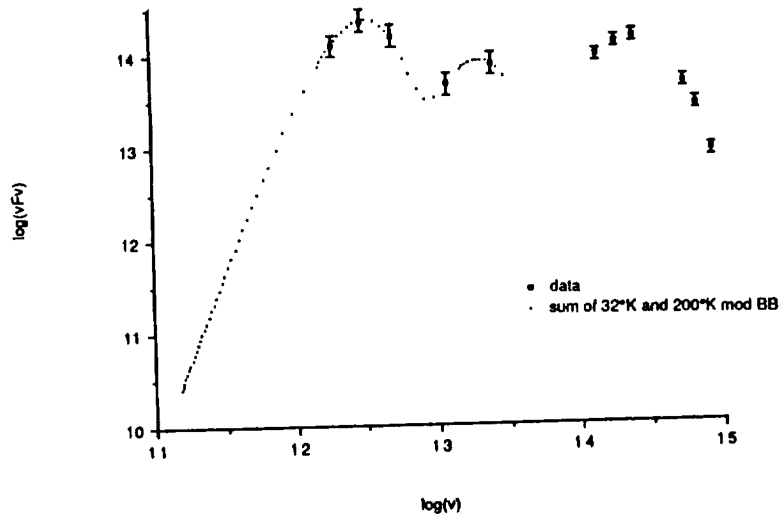

Fig. 4.- Optical/Infrared specrum of the central 45" of NGC 6946. Far-infrared data is from KAO; mid-infrared data is from Rice et al. (1986); and near-infrared and optical is from Rieke and Lebofsky (1979).

The contour map of Hα surface brightness with 45" resolution (figure 3a) has been made from data of Bonnarel et al. (1986). Note the ring of bright HII regions which surrounds the nucleus. The relative Hα radial surface brightness distribution is shown along with the 100/160μm color temperature in figure 5. The 100/160μm color temperature for dust in the nucleus and in the ring is 32°K. The intermediate ring of low Hα surface brightness is 25°K. Figure 3b is a histogram of the number of HII regions versus distance from the nucleus; note fewer are observed at radii where the color temperature is low. We also computed the 100μm optical depth as a function of radial distance from the nucleus by inverting the relation $F_{\upsilon}(r) = \pi B_{\upsilon}[T(r)](1-\exp(-\tau(r)))\Delta\Omega$, where $\Delta\Omega$ is the beam area of our instrument. The radial variation of the 100μm optical depth and the color temperature are plotted in figure 6.

We divided our 100 and 160μm maps by a fully sampled CO(1->0) map with 45" resolution (Tacconi and Young,1987). The ratio of 100 and 160 μm flux to integrated CO(1->0) luminosity is 2/3 higher for the central 2' than for the rest of the galaxy (figure 7). Beyond the central region, the 160μm/CO(1->0) ratio is nearly constant to the edges of the map while the 100μm/CO(1->0) ratio is gradually increasing twoard larger radii. The oscillations in these profiles are very likely due to sampling artifacts in the CO map: the sample points were equally spaced on concentric circles.

Finally, we mention that the ratio of 100μm to Hα intensity rises sharply twoard the nucleus for the regions we mapped. This could be due either to an intrinsic difference in the 100μm to Hα ratio in the radiating source or to increased attenuation of Hα by dust in the nucleus.

IV. Conclusions

We have mapped the nucleus and inner-arm regions of the Scd type galaxy NGC 6946 at 100 and 160μm with an array of 45" beams. From these observations, combined with other published data, we find the following:

1. The dust reemission of NGC 6946 at 100 and 160 microns shows a peak at the center superposed on an exponential disk with a scale-length of 5.6 kpc.
2. The peak is offset 24" NE of the Dressel and Condon optical position. This displacement is over four times our estimated RMS pointing error.
3. Approximately 20% of the flux at 100 microns comes from the central 3 kpc. The percentage of the total 160 micron flux from this region is somewhat smaller.
4. The 100 and 160 micron light follows closely, but not exactly, the Hα; the inner spiral arms have been resolved at both wavelengths, but the structure is clearer at 100 microns.
5. Our analysis shows that the 100/160 micron color temperature is correlated with regions of prominent Hα emission. If a similar process generates all the dust reemission in the far-infrared and the color temperature is representative of the actual dust temperature, this correlation strongly suggests that the the dust is being heated by photons from young, luminous stars.
6. The nucleus is more optically thick at 100 microns than the edge of the disk. An upward inflection of the optical depth occurs at 3 kpc, where the color temperature is a local minimum.
7. The strength of the 100 micron relative to the Hα light increases twoard the nucleus. If the far-infrared flux is reemission of OB stellar radiation, one might expect the two quantities to scale, unless larger concentrations of dust in the nucleus are attenuating the Hα more than in the disk. This is consistent with statement #6. Alternatively, this could be due to an intrinsic difference in the radiating source.
8. The F_{IR}/I_{CO} ratio is fairly constant over the disk but abruptly increases by 2/3 for the central 2' region.

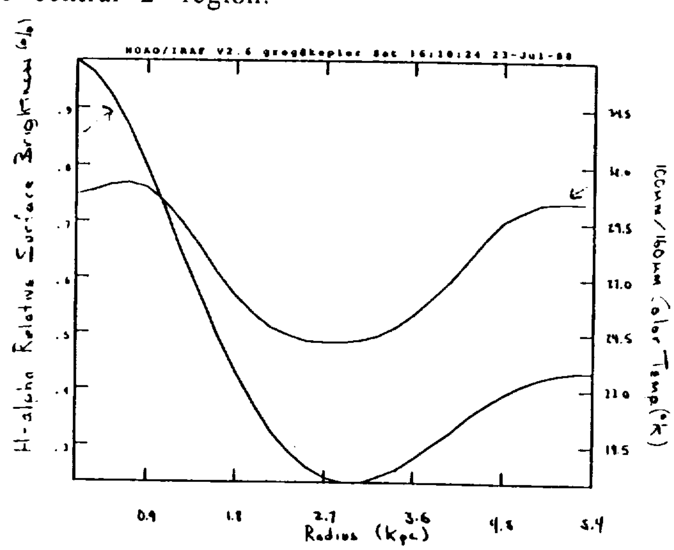

Fig. 5. - The relative Hα radial surface brightness distribution plotted with the 100/160μm color temperature.

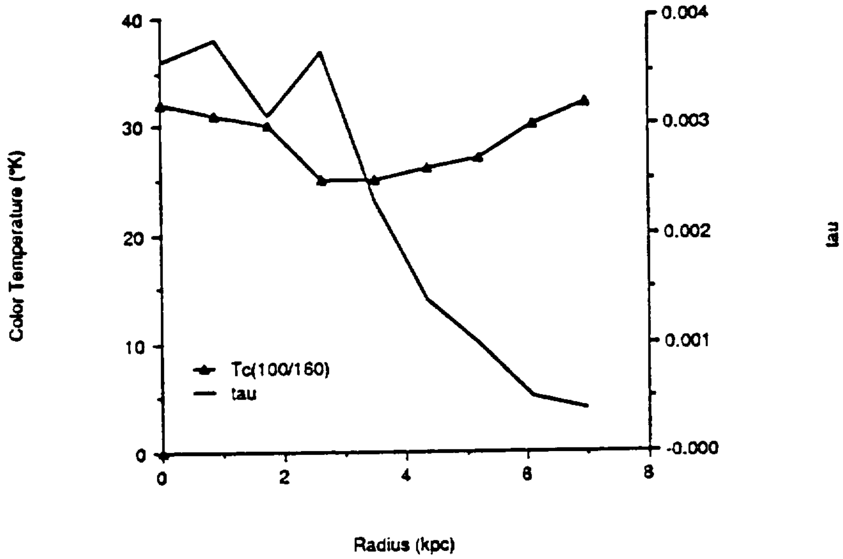

Fig. 6. - The radial variation of the 100μm optical depth and the 100/160μm color temperature.

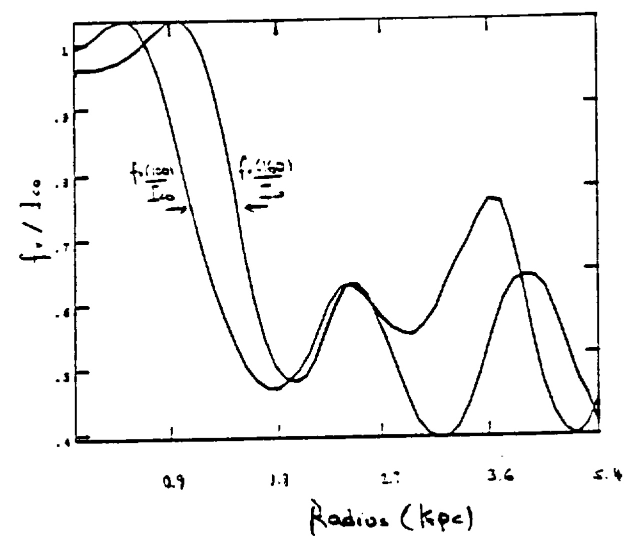

Fig.7. - The ratio of the 100 and 160μm flux to integrated CO(1->0) intensity.

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