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EXTRANUCLEAR X-RAY HEATING OF DUST IN NGC 1068

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RESUMEN

La mayoría de la emisión extensa correspondiente al medio-infrarrojo en NGC 1068 proviene de dos regiones situadas en el eje radial (radio $\approx$ 1 kpc; 15″) y coincide con concentraciones de nubes moleculares en ambos lados del núcleo activo. Un gran número de autores han demostrado que el núcleo de la galaxia Seyfert está radiando anisotropicamente en este mismo eje. Investigamos la posibilidad de que la emisión en el medio-infrarrojo proviene del calentamiento de los granos de polvo en la superficie de la nube molecular causado por los rayos-x del núcleo. En este caso, nuestros modelos proporcionan límites en la luminosidad ionizante del núcleo y de la fracción de energía en las longitudes de onda correspondientes al ultravioleta.

ABSTRACT

Most of the extended mid-infrared emission in NGC 1068 arises from two regions displaced along the radio axis (radius $\approx$ 1 kpc; 15″) and coincident with molecular cloud concentrations on either side of the active nucleus. Many authors have shown that the Seyfert nucleus is radiating anisotropically along this same axis. We investigate the possibility that the extended mid-infrared emission arises from nuclear x-ray heating of dust grains on the surface of molecular clouds. In this event, our models provide constraints on the nuclear ionizing luminosity and on the fraction of energy at UV wavelengths.

Key words: **GALAXIES: INDIVIDUAL (NGC 1068) — GALAXIES: ISM — GALAXIES: SEYFERT**

1. INTRODUCTION

NGC 1068 is one of the most luminous Seyfert galaxies at infrared wavelengths ($2\times10^{11}L_\odot$; 14.1 Mpc) with almost all of the radiation emerging in the $1 - 300\mu$m range. The inner 3 kpc region is dominated by a stellar bar aligned NE–SW (Scoville *et al.* 1988; Thronson *et al.* 1989) and by molecular spiral arms that emanate from the ends of the bar (Planesas *et al.* 1991). For more than a decade, there has been a steady stream of multi-waveband observations providing evidence for extended, extranuclear activity in the direction of the bar, particularly at radio and x-ray wavelengths (Wilson & Ulvestad 1982; Wilson *et al.* 1992). Many authors have shown that the gas along the radio axis is more highly ionized and excited than in the general disk (Balick & Heckman 1979). Notably, Pogge (1988) and Bergeron *et al.* (1989) find that high ionization species (e.g., O^{++}, Ne^{++}, Ne^{4+}) are confined to a fan-shaped region aligned with the radio axis.

In earlier papers, we demonstrated that the inner 10 kpc disk of NGC 1068 shows evidence for an isotropic, diffuse ionized medium (DIM) with an implied cooling rate of $\approx 2\times10^{44}$ erg s^{-1} (Bland-Hawthorn *et al.* 1991). Two distinct mechanisms have been proposed to explain the DIM phase. Sokolowski *et al.* (1991) contend that the same electron-scattering medium that gives rise to both the observed x-ray spectrum and the polarized broad-line spectrum can produce a dilute, hard ionizing continuum that is sufficiently energetic to power the low ionization emission. Slavin *et al.* (1993) have considered the coronal emission arising from the turbulent 'mixing layers' in the multiphase ISM which naturally produces strong, low ionization lines. Halpern (1992) has suggested that the extended x-ray disk observed by ROSAT (Wilson *et al.* 1992) may not be sufficient to balance the cooling rate of the DIM, and reiterates that the active nucleus could be an important source of ionizing radiation. This has motivated us to search for a robust constraint on the unobscured ionizing luminosity in NGC 1068 which we now describe.

2. THE ORIGIN AND DISTRIBUTION OF THE MID-INFRARED EMISSION

Telesco & Decher (1988) have shown that almost all of the $\lambda 10.8\mu$m emission occurs in two diametric 'plumes' at roughly 15″ radius along a NE–SW direction. The mid-infrared emission is clearly associated with the dense CO arms (Planesas *et al.* 1990), and shows some association with two of the brightest HII region complexes in the region scanned by the bolometer (Telesco & Decher 1988, Fig. 3). However, we note that strong $\lambda 10.8\mu$m emission is not detected in the NE complex (radius $\approx 25''$) nor in the NW complex at 10″ radius, both of which fall within the scanned region (Telesco 1993, personal communication). A detailed dynamical study by one of us (J.B.H.) finds that the azimuthal spread around the bar of Hα emission regions is out of phase with the main sites of CO emission. While the resolution of the mid-infrared data is not high ($\approx 10''$ FWHM), the $\lambda 10.8\mu$m emission correlates better with the CO than with the Hα emission.

From a reanalysis of the VLA data presented by Wynn-Williams *et al.* (1985), we are unable to find any correlation between the $\lambda 10.8\mu$m emission and the underlying $\lambda\lambda 2-20$cm continuum. When compared with HII regions, the ratio of $\lambda 10.8\mu$m to radio cm band emission is high ($20-50$), regardless of how we interpret the radio emission. Thronson, Campbell, & Harvey (1978) find a tight relation between 11μm and cm-wave flux densities for high surface brightness galactic HII regions and molecular cloud complexes. They find $S_\nu(11\mu\mathrm{m})/S_\nu(\mathrm{cm}) = 10 \pm 3$ for a sample of $\sim$40 objects. In larger HII region complexes and starburst galaxies, the synchrotron emission starts to overwhelm the free-free emission at around $\lambda 2$ cm (Condon & Yin 1990), primarily because the star forming regions are now sufficiently large that stars are not able to migrate out of the region by the time they reach the supernova stage.

We note with interest that the angular extent of the $\lambda 10.8\mu$m plumes coincides nicely with the angular extent of both the O^{++} (Pogge 1988) and the soft x-ray emission (Wilson *et al.* 1992). Telesco *et al.* (1980) originally considered the idea that the extended infrared emission could arise from dust heated by the active nucleus. At that time, it did not seem possible that dust could be maintained at a high color temperature (70–160 K) over a distance of a kiloparsec. There are two good reasons to revisit this model. First, one of us (G.M.V.) has recently developed detailed models to examine the impact of an x-ray radiation field on a population of dust grains. Secondly, ionizing radiation is now known to be escaping from the Seyfert nucleus through an opening angle that intersects the plane of the galaxy (Cecil *et al.* 1990). It so happens that this solid angle encompasses the mid-infrared 'plumes' and associated molecular clouds.

3. X-RAY HEATING OF DUST GRAINS

In recent papers, one of us (G.M.V.) has considered how high energy photons heat and evaporate dust grains in molecular clouds (Voit 1991; 1992). We now use the models to examine the possible impact of the Seyfert nucleus on molecular gas along the radio axis in NGC 1068. Mathis, Rumpl, & Nordsieck (1977; MRN) have presented a dust grain model that successfully explains the 'standard' extinction curve in terms of the absorption and scattering properties of graphite and silicates. We adopt their power-law distribution of grain sizes, $dn = (A_{\mathrm{Si}} + A_{\mathrm{C}})\, n_H\, a^{-3.5}\, da$, within the range $5\text{Å} \leq a \leq 0.5\mu$m normalized to the gas density, n_H. The abundances for the silicates, A_{Si}, and for graphite, A_{C}, assumed to be 100% carbon, are given elsewhere (Voit 1991).

We examine the influence of three different ionizing continua: a power law with monochromatic flux $f_\nu \propto \nu^{-1}$, and thermal bremsstrahlung spectra at temperatures of 0.2 and 5 keV. Voit (1991) has shown that the most crucial parameter is the x-ray flux incident on the molecular cloud, $F_{\mathrm{in}} = \int f_\nu\, d\nu$. We consider flux levels of $10^8, 10^4$, and 10^2 erg cm^{-2} s^{-1} equivalent to placing a molecular cloud at distance of 1 pc, 100 pc, and 1 kpc respectively from a 10^{46} erg s^{-1} ionizing source. Further, we consider flux levels of 10, 1, and 0.1 erg cm^{-2} s^{-1} for a cloud at 1 kpc from ionizing sources of $10^{45}, 10^{44}$, and 10^{43} erg s^{-1} respectively. The re-radiated ionizing flux is given by

$$F_{\mathrm{out}} = \epsilon\, (\Delta\Omega/4\pi) \int_{\nu_0}^{\nu_1} f_\nu e^{-\sigma_\nu N_H} d\nu \tag{1}$$

where ϵ is the sky coverage fraction within the total solid angle $\Delta\Omega/4\pi$ subtended by the molecular clouds, as seen from the nucleus. If we assume a cylindrical geometry, the molecular gas coincident with the $\lambda 10.8\mu$m emission (Planesas *et al.* 1991) lies within $\Delta\Omega/4\pi = 0.1$; the enclosed mass of gas is roughly $1.5 \times 10^9 M_\odot$.

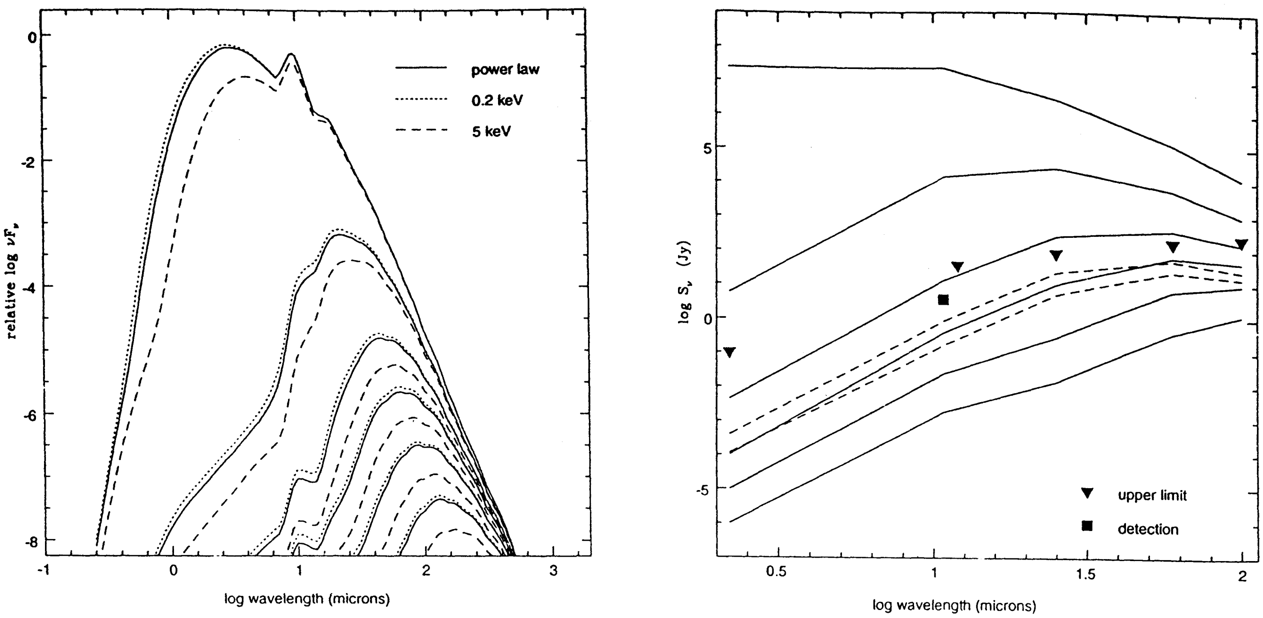

Fig. 1. — (a) The relative energy spectra arising from dust irradiated by 3 different x-ray continua at flux levels of $10^8, 10^4, 10^2, 10, 1, 0.1$ erg cm^{-2} s^{-1} (top to bottom). (b) The predicted near- to far-infrared spectra for the $\lambda 10.8\mu$m features. The solid lines are computed from the power-law models, with the highest flux level at the top, as in (a). The filled triangles indicate upper limits for the K band and four IRAS bands. The filled square is the detection of Telesco & Decher (1988). The dashed lines correspond to flux levels of $10^{1.1}$ and $10^{0.6}$ erg cm^{-2} s^{-1} and include an additional UV component as explained in the text.

At a distance of 1 kpc from the AGN, the projected mass of gas corresponds to $N_H \sim 1.5 \times 10^{23}$ cm^{-2} ($\epsilon = 1$). For a Galactic dust to gas ratio, half of the total power in x-rays is absorbed by the dust and then re-radiated in the infrared. The remaining half absorbed by gas-phase atoms excites an equivalent luminosity in UV radiation which also heats the dust grains. Voit (1991) finds that the grains are opaque to UV radiation, while being translucent to x-rays. Since most of the surface area of the MRN composition lies in the small grains, these are predominantly UV heated. The x-rays require a significant stopping column and therefore heat the large grains preferentially. The temperature distribution of the grains directly determines the form of the re-radiated spectrum. The smallest grains, after absorbing individual photons, can superheat to temperatures more than an order of magnitude higher than their equilibrium temperatures (Puget & Leger 1989) before cooling down again. These 'flickering grains' give rise to broad temperature distributions. X-ray photons can evaporate the smallest grains ($a \leq 8$Å) on a very short timescale through repeated superheating to temperatures in excess of 2000 K.

4. DISCUSSION

In Fig. 1, we present the results of the calculations. The limits of integration in equation (1) are taken to be $\nu_0 = 100$ eV/h and $\nu_1 = 10$ keV/h. In Fig. 1(a), the re-radiated spectrum is clearly a strong function of the x-ray flux incident upon the molecular gas (Voit 1991); the spectral shape is of secondary importance. The power-law models have been used to compute the expected flux arising in the K band, $\lambda 10.8\mu$m band and four IRAS bands, shown by the solid lines in Fig. 1(b). The far-infrared emission provides a strong constraint on an x-ray heating model. In particular, a flux of 40 erg cm^{-2} s^{-1} can explain the $\lambda 10.8\mu$m emission at the expense of predicting too much far-infrared emission. A flux level of 10 erg cm^{-2} s^{-1}, equivalent to putting all of the bolometric luminosity within our x-ray band, falls short by an order of magnitude in explaining the mid-infrared emission.

There are two ways in which the re-radiated mid-infrared emission can be enhanced at the expense of the far-infrared emission. First, if a significant fraction of small grains ($\leq$ 10Å) are able to survive, their broad temperature distributions, while undergoing thermal transients, can selectively enhance the near-infrared flux. Secondly, the models discussed so far do not include a direct UV component, nor do the models consider the UV and optical emission expected to arise in the gas phase around the x-ray heated grains. To address the role of UV, we adopt $\nu_0 = 10$ eV/h in equation (1) and enhance this component by a factor of ten compared with x-rays. The resulting spectra are shown as dashed line models in Fig. 1(b). At a flux level of 30 erg cm^{-2} s^{-1}, such a model could reasonably explain the λ10.8μm detection at the same time as falling within the limits imposed by the IRAS measurements. However, this does require a proportion of the UVX radiation to be beamed along the radio axis. While our enhanced UV model is somewhat arbitrary, 'big blue bumps' are commonly observed in quasar spectral energy distributions (e.g., Sanders *et al.* 1989).

The factor ϵ allows for clumpiness within the solid angle seen from the nucleus. For a typical AGN spectrum, $F_{\rm out}$ will depend much more sensitively on ϵ than on N_H at column densities of 10^{23} cm^{-2}. By way of example, if we take $\epsilon = 0.3$, increasing N_H by a factor of 3 allows the cloud to absorb the X-ray power between about 3 keV and 5 keV, but this is a small fraction of the total power. In the present models, we do not consider self-absorption of the near- to mid-infrared emission by the dusty medium. The details of this correction depend on the cloud-source geometry and obviously depends on whether we are viewing the irradiated or back surface of the molecular cloud. For the measured column density, this is more critical for the K band where the extinction correction is expected to be $\sim$ 10 mag compared to $\sim$ 0.1 mag at λ10μm.

In our view, there is no compelling reason to rule out dust heated at a distance by nuclear radiation. As noted by Wynn-Williams *et al.* (1985), other possible interpretations include $\lambda\lambda3.3 - 11.3\mu$m line emission from polyaromatic hydrocarbon (PAH) molecules. However, for the x-ray fluxes considered in our models, PAH molecules should be destroyed (Voit 1992). In either event, we anticipate that the equivalent widths of mid-infrared emission lines will provide a strong diagnostic on the heating mechanism and therefore set constraints on the nuclear luminosity. A more detailed description of these results is to appear elsewhere.

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