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WARM AND COLD GAS IN GALACTIC NUCLEI: THE NEAR-IR/MILLIMETER CONNECTION IN NGC 253

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ABSTRACT We discuss the use of seeing-limited near-IR spectroscopic imaging combined with high resolution millimeter and submillimeter wave observations, as a diagnostic in the study of the nuclear interstellar medium in starburst galaxies and active galactic nuclei. As an example, recent near-IR spectroscopic imaging of the starburst galaxy NGC 253 is analyzed. It is shown that the central $\sim$ 100 pc of NGC 253 contains a number of giant star forming complexes, the stellar content of which is at least as large as that of the 30 Dor region in the LMC. We suggest the use of the [Fe II]/Br γ ratio as an approximate age indicator for such complexes. The warm component of the nuclear molecular medium in NGC 253 detected in submillimeter CO spectra and in near-IR rovibrational lines of H_2 is probably heated by stellar UV radiation or slow shocks in star forming regions, rather than by supernova remnant shocks. There are indications that molecular material is being removed from the nuclear region by the "superwind" observed in optical emission lines.

INTRODUCTION

With modern millimeter wave synthesis arrays arcsecond resolution can now routinely be achieved (e.g., Scoville, this volume). In addition, with the recent advent of low read-noise array detectors, seeing-limited imaging of near-infrared spectral lines has become possible. With arcsecond resolution it is feasible to resolve molecular concentrations and star forming regions in active galactic nuclei (AGNs) and starburst galaxies in the local universe. While millimeter wave spectral lines typically trace cool or moderately warm material, in the near-IR warm to hot gas is observed. The most important near-IR spectral lines observed

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in galactic nuclei are listed below.

- The Br γ line (2.166 μm) directly traces gas photoionized by stellar UV radiation or by the UV/X-ray continuum from an active nucleus.
- The H_2 $v = 1 \rightarrow 0$ S(1) line (2.121 μm) can be produced by warm UV-irradiated molecular gas producing thermal or fluorescent emission in the H_2 near-IR rovibrational lines (e.g., Sternberg and Dalgarno 1989), by collisionally excited gas in molecular shocks (Draine et al., 1983) or molecular gas exposed to large soft X-ray fluxes (Draine and Woods 1990).
- The [Fe II] $a^4D_{7/2} \rightarrow a^4F_{9/2}$ line (1.644 μm) and other near-IR lines of this ion trace partially ionized gas in fast ($v = 100 - 200\,\mathrm{km\,s^{-1}}$) shocks or in X-ray photoionized nebulae (e.g., Sternberg 1992). Particularly luminous sources of [Fe II] 1.644 μm emission are supernova remnants (e.g., Oliva et al. 1989), and the line has also been observed in some Herbig-Haro objects (Stapelfeldt et al. 1991). SNRs can have total luminosities in the [Fe II] 1.644 μm line of almost $10^3\,L_\odot$, but some are several orders of magnitude less luminous (Oliva et al. 1989). In fast shocks the [Fe II] emission may be enhanced by the destruction of refractory grains by thermal sputtering, leading to an enhancement in the gas phase abundance of iron of up to a factor of 30 (e.g., Seab and Shull 1983, McKee et al. 1987).
- The [Si VI] (1.962 μm) and [Si VII] (2.481 μm) lines trace a medium of high ionization and excitation that is presumably closely related to an embedded AGN. These so-called *coronal* lines have been detected in Seyfert nuclei (e.g., Oliva and Moorwood 1990, Moorwood and Oliva 1991).

The combination of these lines with high resolution millimeter and submillimeter observations is clearly a powerful tool in the study of the interaction of stars or active nuclei with the ambient molecular gas. In this paper we present recent seeing-limited near-IR spectral line imaging of the nearby starburst galaxy NGC 253. The near-IR data were obtained with the MPE near-IR camera FAST (Rotaciuc 1992).

NGC 253

NGC 253 is a nearby ($D = 2.5$ Mpc, $1'' = 12$ pc) starburst galaxy, seen almost edge-on. Canzian et al. (1988) have presented a ^{12}CO $1 \rightarrow 0$ map of the central molecular gas concentration in NGC 253, which shows that the nuclear molecular medium is concentrated in a $40'' \times 10''$ bar-like structure containing about $5 \times 10^8\,M_\odot$ of molecular gas. HCN and HCO^+ observations show a morphology very similar to that of CO (Carlstrom 1990), indicating that most of the nuclear medium in NGC 253 is dense ($n_{H_2} \gtrsim 10^4\,\mathrm{cm^{-3}}$). Submm observations of CO isotopes (Wall et al. 1991, Harris et al. 1991) indicate that close to the nucleus a substantial fraction ($\sim 50\%$) of this material is warm with kinetic temperatures of at least 50 K. The mean column density over the area of the nuclear molecular bar is $N(H_2) \sim 8 \times 10^{22}\,\mathrm{cm^{-2}}$, corresponding to an average visual extinction of about 40^m towards the nuclear region, assuming that 50% of the molecular

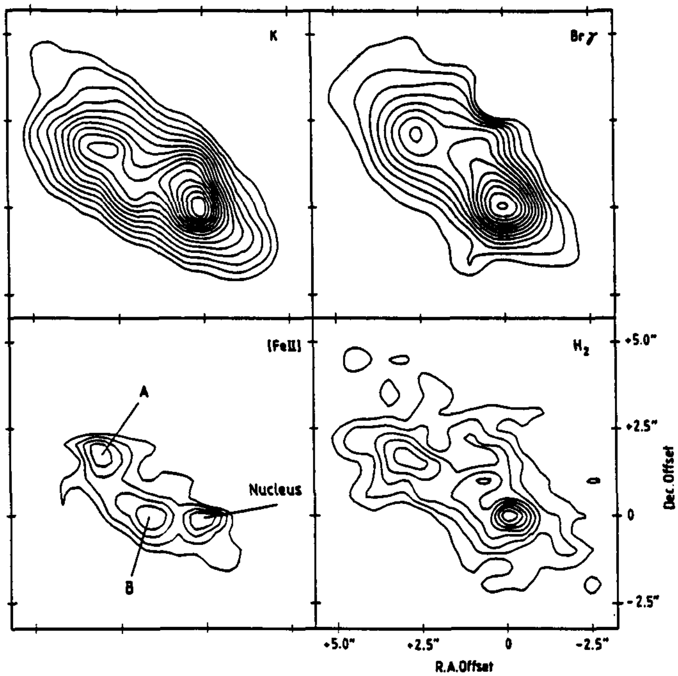

FIGURE I Contour representations of the nuclear region of NGC 253 in K band continuum, Br γ, [Fe II] 1.64 μm and H_2 1→0 S(1) emission. The contours are in units of 2.4, 14 and 2.6 × 10^{-5} erg s^{-1} cm^{-2} sr^{-1} for respectively Br γ, [Fe II] and H_2 emission.

material is located in front of the nucleus. Peak values near the nucleus may be even higher (Canzian et al. 1988).

This large extinction makes it impossible to observe directly the origin of the high nuclear far-IR luminosity ($\sim 1.5 \times 10^{10}\, L_\odot$ in the central ~ 400 pc, Telesco and Harper 1980) in the optical regime. However, in the near-IR this problem is significantly alleviated. In Fig. 1 we show near-IR images of the nuclear region of NGC 253 in the K band continuum, and the Br γ, [Fe II] 1.64 μm and H_2 1→0 S(1) spectral lines (Forbes et al. 1993). Spatial resolutions are 1.3″ for Br γ and 0.9″ for the other images. No emission is detected from the region south-west of the nucleus, presumably a result of enhanced extinction in this area (Canzian et al. 1988, Waller et al. 1988).

Taking into account the lower resolution of the Br γ image, the H_2 1→0 S(1) emission in NGC 253 traces the Br γ emission well, and in particular resembles more the Br γ emission than the [Fe II] 1.64 μm emission. This agreement suggests heating or UV-pumping in molecular interface regions exposed to stellar UV radiation, or slow shocks in star forming regions as the most likely excitation mechanisms for the H_2 emission. Shock excitation by SNRs is unlikely since in this case the H_2 emission would be expected to follow the [Fe II] 1.64 μm emission, which traces SNRs (see above). The mass of hot H_2 is about 100 $M_\odot$

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(assuming a temperature of 2000 K), which is only a very small fraction of the total molecular mass in the same region. The mechanism producing this hot material is probably also responsible for the presence of the warm ($T \gtrsim 50$ K) molecular gas (Wall et al. 1991, Harris et al. 1991).

At low brightness levels the H_2 emission shows filamentary structures extending towards the north and reaching projected distances of $\sim$ 50 pc from the plane of NGC 253. These structures may originate in gas entrained in and shocked by the "superwind" in NGC 253 resulting from multiple supernova explosions in the nuclear region, that has been observed in Hα emission and in X-rays (Fabbiano and Trinchieri 1984, McCarthy et al. 1987; Heckman et al. 1990). Molecular material in this superwind is probably also responsible for the "plume" of OH 18 cm emission extending 1.5 kpc from the plane of NGC 253 and presumably ejected from the nucleus (Turner 1985). Evidence for molecular material in superwinds has also been found in NGC 3079 (Irwin and Sofue 1992) and NGC 6240 (Van der Werf et al. 1993).

The [Fe II] emission is dominated by three peaks, two of which (the nucleus and source "A") have point-like counterparts in high resolution radio continuum images (e.g., Ulvestad and Antonucci 1991). A number of radio sources do not have counterparts in the [Fe II] image, consistent with the fact that not all SNRs are luminous in the [Fe II] line (Oliva et al. 1989). The three [Fe II] peaks in Fig. 1 each have a total luminosity of a few $10^3\,L_\odot$ in the 1.64 μm line, consistent with the presence of a few SNRs luminous in [Fe II] in every peak.

Comparison of the near-IR data with starburst models shows that each of the observed peaks is a gaint (10 – 50 pc) star forming complex containing a mixture of HII regions, SNRs and giant molecular clouds. Each complex contains a few 10^3 OB stars (as inferred from Brγ) and a few SNRs (inferred from radio continuum and [Fe II] emission). The red supergiants created in these star forming regions can account for more than half of the observed K band continuum flux (Forbes et al. 1992). This conclusion is in agreement with the strength of the CO absorption bands at 2.3 μm (Doyon et al. 1991), which originate in the extended envelopes of red supergiants. For each peak the total luminosity is almost $10^9\,L_\odot$ and the star formation rate is $\sim 0.5\,M_\odot\,yr^{-1}$. With these parameters the observed peaks are very similar to the giant star forming complex 30 Dor in the LMC. The different [Fe II]/Brγ ratios found for the various peaks may be related to different evolutionary stages of the complexes: after the termination of massive star formation the most massive stars first evolve off the main sequence, leading to a precipitous decrease in the production of Lyman continuum photons, and a corresponding decrease in Brγ luminosity. The supernova rate however, is dominated by stars of about 8 – 10 $M_\odot$ and thus remains high for a few times 10^7 years after the termination of massive star formation. Thus in this model the complexes with the highest [Fe II]/Brγ ratios are most evolved.

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DISCUSSION

Q: Z. Wang In NGC 1068, you mention the heating for H_2 and [FeII] lines is due to the X-ray from the AGN. Is that mostly based on morphological appearance?

A: P. van der Werf Yes. You can compare the H_2 and Fe line images with that of Brγ, they seem to be quite different, so H_2 and Fe do not seem to be heated by H II regions/star formation. On the other hand, models by Draine and Woods seems to indicate the AGN is quite capable to do the heating.

Q: L. Avery Can you comment on why some SNRs are not bright in the [Fe II] line and others are? Is it because of chemistry or excitation effects?

A: P. van der Werf A SNR with a luminosity of almost 10^3 $L_\odot$ in the [Fe II] 1.64μm line alone must be in the snowplough phase, where cooling by line emission dominates. The [Fe II] luminosity of a SNR in this phase depends then strongly on the gas phase abundance of iron. This parameter depends on the efficiency of the destruction of refractory grains in the blast wave shock during the snowplough phase and earlier, which in turn depends on the parameters of the ambient medium. Thus both the evolutionary stage of the SNR and the properties of the ambient medium play a role. Radio emission however, is observed throughout the evolution of the remnant, and its brightness is governed by completely different parameters (e.g., Chevalier 1981, ApJ, **251**, 259). Therefore the lack of a detailed correspondence between [Fe II] and radio emission is not surprising if individual SNRs are considered. A starburst nucleus on the other hand will contain a collection of SNRs in various stages of evolution and interaction with the ambient medium. [Fe II] observations of starburst nuclei select only that fraction of all SNRs that happens to be luminous in the [Fe II] line at the epoch of observation. In as far as this fraction is constant, the [Fe II] luminosity is proportional to the supernova rate. To put these arguments on a more quantitative foundation, a theoretical study of the [Fe II] emission from an individual SNR as a function of time and with different parameters for the ambient medium would be very important for the interpretation of the [Fe II] emission from starburst galaxies.

Q: H. Zinnecker How does the distribution of Br gamma in NGC 253 compare with that of Hα and what is the velocity width of Brγ?

A: P. van der Werf Hα is too extincted to yield any information about the nuclear region observed in Brγ. The extended extranuclear Ha emission regions, in particular off the equatorial plane, are too faint to produce any detectable Brγ emission. At our velocity resolution of 300 kms^{-1} Brγ is unresolved. This is consistent with the measured Hα line width of about 200 kms^{-1} (Busko and Steiner 1990, MNRAS, **245**, 470), although this agreement is probably not very meaningful, since Hα and Brγ do not really trace the same gas.

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