ISO-SWS OBSERVATIONS OF NGC 1068

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Abstract. We present a first analysis of 2.4-45μm spectra of NGC 1068 obtained with the Short Wavelength Spectrometer SWS on board the Infrared Space Observatory ISO. The measured fine-structure line fluxes can be fit successfully by a simple photoionization model invoking an EUV bump in the ionizing continuum, similar to the case of the Circinus galaxy. Difference are observed between the [O IV] 26μm NLR line profile and optical NLR line profiles which may indicate significant extinction to part of the NLR. We detect pure rotational transitions of molecular hydrogen that must be emitted by molecular gas spanning a wide range of temperatures. The unusual strength of the fundamental S(0) 28μm rotational transition is evidence for a large ($> 1.5 \times 10^9 M_\odot$) gas mass at temperatures near 100 K. Either most of the gas in the circumnuclear region of NGC 1068 is warm or previous molecular mass estimates based on CO observations were too low. Strong mid-infrared continuum from the circumnuclear warm dust is prominent in our spectrum. The weak PAH emission detected at the edges of the 9.7μm silicate absorption should be considered in interpretations of the silicate feature.

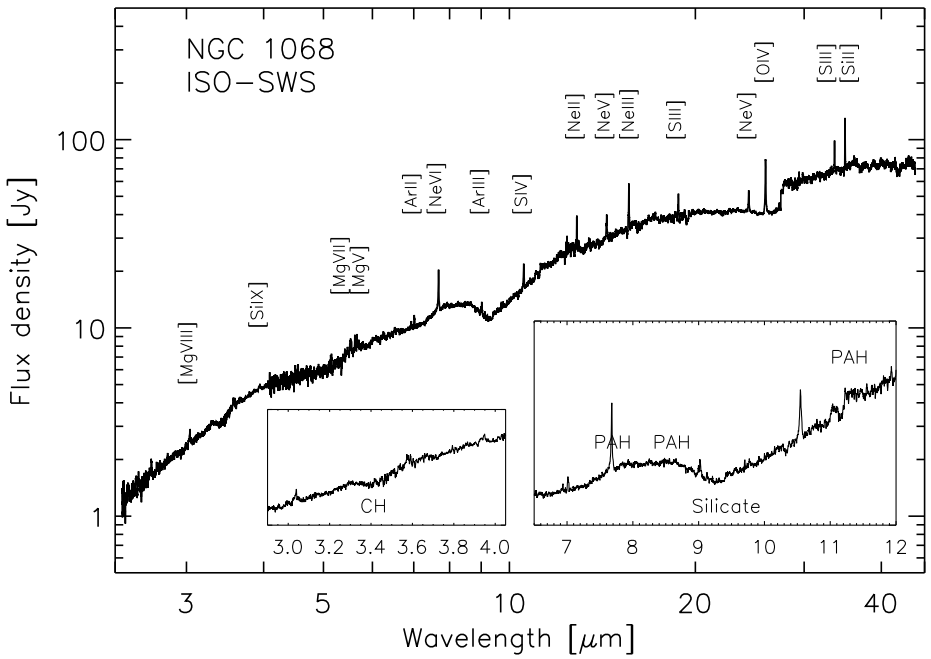

Figure 1. ISO-SWS spectrum of NGC 1068

1. Introduction

The advent of the ISO satellite has opened the possibility of sensitive mid-infrared spectroscopy of active galactic nuclei. The 2.5-45μm range contains fine-structure transitions of many ionization stages of abundant elements. They provide excellent diagnostic tools for ionized media. Pure rotational lines of molecular hydrogen provide the first direct measurement of the bulk constituent of warm molcular gas, and [Fe II] transitions trace partially ionized zones.

NGC 1068 was observed with ISO-SWS on August 28, 1996. We present first results from a 2.4-45μm full SWS spectrum, and deeper spectra centered on individual H_2 rotational transitions. A more detailed analysis is deferred to a forthcoming paper which will also include more observations of fine-structure lines that are planned for later in the mission. Diffraction in the ISO telescope requires large entrance apertures, for SWS they range between 14"$\times$20" at the shortest and 20"$\times$33" at the longest wavelengths. The apertures were oriented almost north-south (PA -11.6^o), thus part of the star-forming arms is included at the longest wavelengths. Data were analysed using the SWS interactive analysis software. The full SWS spectrum consists of various segments obtained with different instrument

configurations, some of which were slightly scaled to minimize jumps.

2. The 2.5-45μm spectrum

The continuum shape of the SWS spectrum (Fig. 1) is dominated by the central mid-infrared source and hence similar to the SED measured for the central few arcseconds by ground-based photometry (e.g. Lebofsky et al. 1978). Features detected include the 3.4μm CH absorption (see also Bridger et al. 1994) and the 9.7μm silicate absorption. On both sides of the 9.7μm silicate absorption, we detect weak PAH emission (7.7, 8.6, 11.3μm). 3.3μm PAH emission is not unambiguosly detected due to signal-to-noise and interference with the nearby CH absorption. The PAH emission is weak probably due to destruction of the PAH molecules in the intense AGN radiation field (e.g. Roche et al. 1991). The 8.6μm feature is similar in strength to the 7.7μm one, while the 11.3um feature is relatively faint. Observations of PAHs in H II regions (Roelfsema et al. 1996, Verstraete et al. 1996) indicate that this may reflect a particularly intense radiation field. An alternative interpretation of the emission features on both sides of the silicate absorption might be simply wings of a wide emission maximum split by the absorption from the silicate feature (e.g Pier & Krolik 1992). However, we consider this unlikely due to the detailed shape of the emission features, e.g. the sharp onset near 7.3μm, the 7.7/8.6 double peak, and the split 11.3μm feature, all matching PAH observations in other sources. Some of the PAH emission may just be picked up by the large SWS aperture, although the match in shape with the ground-based data of Roche et al. (1984) for the 8-13μm range suggests this effect to be of minor importance. A cautionary note applicable to NGC 1068 as well as to other galaxies is that the apparent depth of the 9.7μm silicate absorption feature may often be overestimated in the presence of adjacent PAH emission. Ground-based 8-13μm data suffer from this problem in particular if the 7.7/8.6μm complex is strong compared to the 11.3μm feature, as is the case for NGC 1068.

3. The ionizing continuum

We detect fine-structure line emission from various ionization stages of Neon, Oxygen, Argon, Sulphur, Silicon, and Magnesium. Mid-infrared fine-structure lines are robust probes of photoionized gas since they are insensitive to electron temperature and to dust extinction. The fine-structure lines span a wide range of ionization energies (up to 300eV). Observations of several ionization stages of the same element may be used to probe the ionizing radiation field with little sensitivity to abundance effects. Moorwood et al. (1996) have used a similar dataset to determine a photoionization model for the Circinus galaxy. They were able to successfully fit ISO and near-

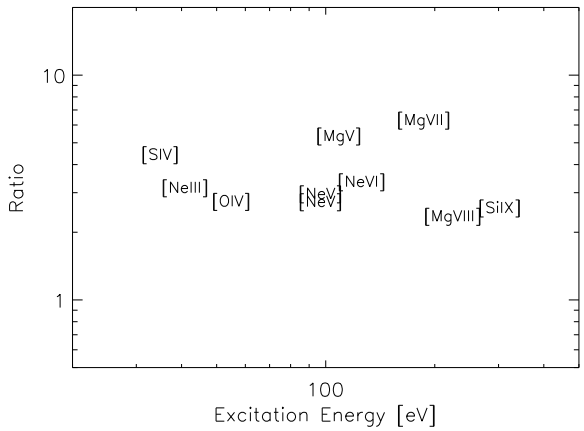

Figure 2. Ratio of observed fine-structure line fluxes in NGC 1068 to the fluxes measured for Circinus by Moorwood et al. (1996). The NGC 1068 spectrum is quite similar to the Circinus spectrum that was successfully modelled using an ionizing continuum with an EUV bump.

infrared observations with a simple model invoking an EUV bump in the ionizing continuum peaking at about 70eV. The bump could equally well be represented by a blackbody-like component peaking at this energy or by a *broken* power law of similar shape. A simple ratio of observed line fluxes in NGC 1068 and Circinus (Fig. 2) indicates that a very similar model should be successful for NGC 1068 - in fact the line fluxes observed in NGC 1068 can be fit by a scaled 'Circinus' model within a factor of 2. Photoionization models based on the ISO lines hence provide the exciting opportunity to constrain the ionizing continuum shape in the unobservable EUV range. This method can be applied to Seyfert 2 galaxies with significant extinction like NGC 1068 as well as to Seyfert 1 galaxies for which there already exists direct evidence for the 'edges' of the EUV bump in the UV and soft X-ray (e.g. Walter et al. 1994).

4. Line profiles

The measured mid-infrared line profiles in NGC 1068 can be split into three groups: a) narrow emission of molecular hydrogen (see following section), b) narrow emission from low-excitation fine-structure lines, and c) wider medium- to high excitation fine-structure lines from the AGN Narrow Line Region. Group b) includes [S III] 33.5μm and [Si II] 34.8μm which are measured with the largest aperture and the beam-profile most broadened by diffraction, most likely they are dominated by emission from the star-forming arms. [Ne II] 12.8μm and [S III] 18.7μm are of lower signal-to-noise

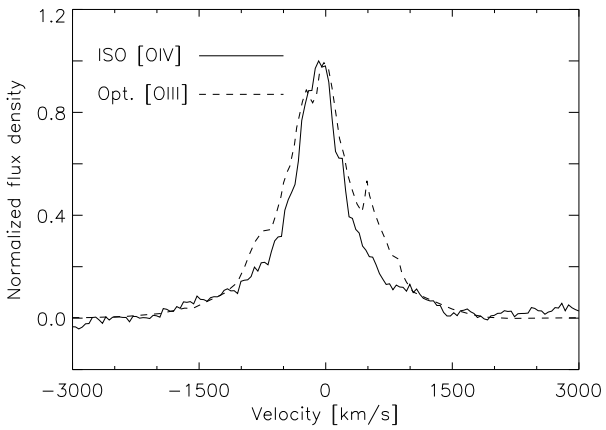

Figure 3. Normalized line profiles of the 26μm [O IV] line observed by ISO, and of the 5007A line of [O III] (taken from Veilleux 1991)

but appear narrow as well.

The NLR/coronal lines of group c) from [Ne III] to [Si IX] appear to have identical profiles within the signal-to-noise of the current data, we hence limit our discussion to the [O IV] 26μm line profile which is of the best quality. Figure 3 is an overlay of this profile with the optical [O III] NLR profile of Veilleux (1991), similar comparisons are obtained with other published optical profiles. It is evident that the ISO NLR profile is different from the optical one: while both profiles exhibit wide wings out to at least $\pm$1500 km/s, the core of the ISO profile is significantly narrower. The ISO lines are well fit by the sum of two gaussians with FWHM 500 and 1700km/s contributing approximately 40%/60% to the total flux. At first glance, one could suspect the difference in line profiles to be a simple aperture size effect, integration over similar apertures in optical spectral line datacubes (e.g. Cecil, this volume) indicates however that the contribution of the ENLR is small and the resulting total optical line profile is very similar since it is dominated by the inner few arcseconds of the NLR. Further evidence comes from comparison with the UV data of Kriss et al. (1992) which were obtained with an aperture similar to the ISO one. Their spectra do not appear to show the narrow core and wide wing, but are dominated by a wide component. All this leads us to the suggestion that the part of the NLR corresponding to the narrow core in the ISO profile is observed through significant extinction. 'Significant' refers here to the optical regime - several magnitudes in A_v would be entirely sufficient to induce the observed differences, and the mid-infrared lines themselves may be very little affected. Such a scenario of inhomogeneous extinction is furthermore consistent with the difference between very low extinction found in the UV

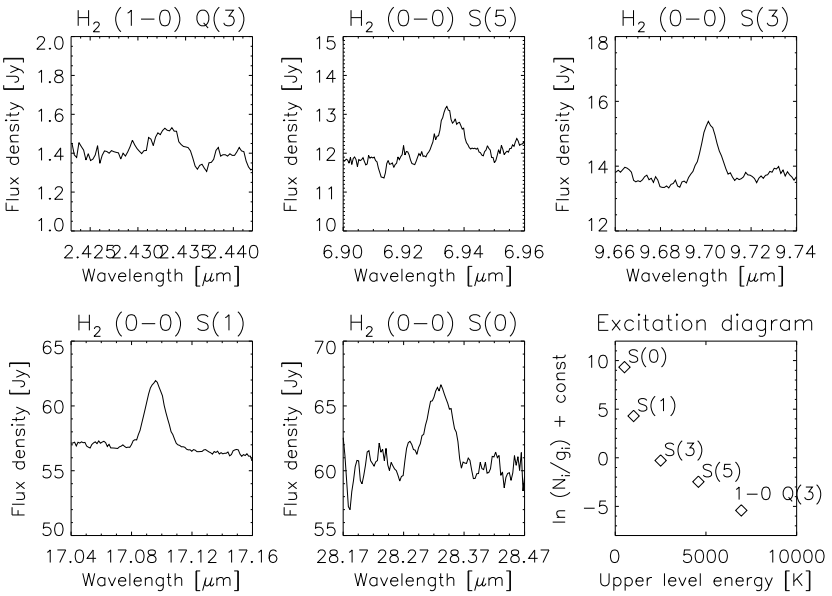

Figure 4. Molecular hydrogen observations of NGC 1068. The excitation diagram in the lower right demonstrates that several temperature components are present.

(Kriss et al. 1992) and higher extinction derived from the Balmer decrement - apparent extinction values that increase with wavelength are the classic signature of inconsistency with a simple foreground screen. Differences between the ISO and optical/UV profiles may also occur if distinct kinematic components are distinct in their electron temperature as well, since the optical/UV transitions are more sensitive to electron temperature.

5. Warm molecular hydrogen emission

The well-known near-infrared rovibrational transitions of molecular hydrogen originate in hot (>1000 K) gas or are excited non-collisionally. Direct detections of warm (100-1000 K) molecular hydrogen in external galaxies are now possible with ISO through the mid-infrared pure rotational transitions. In NGC 1068, we have observed the S(0), S(1), S(3) , S(5), and the rovibrational (1-0) Q(3) transitions (Fig. 4). The derived excitation diagram demonstrates that these lines must trace gas components at a wide range of temperatures - all points would have to fall on a straight line for a single temperature and LTE, while the observed curvature indicates a range from ∼100 K for gas emitting S(0) to ∼800 K for the higher transitions. The same general behaviour is seen in other starbursts and active galaxies ob-

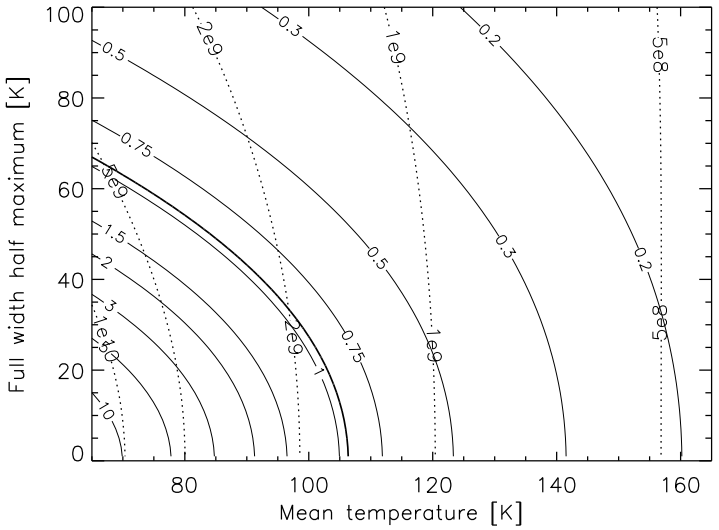

Figure 5. Molecular hydrogen S(0)/S(1) line ratio and gas mass for NGC 1068. A gaussian temperature distribution of the molecular gas was assumed. As a function of mean and FWHM of this distribution, continuous lines present the inferred S(1)/S(0) ratio assuming ortho/para in local thermodynamical equilibrium. The thick continuous line marks the observed ratio. The dashed lines indicate, for the specific case of NGC 1068, the total mass required to produce the flux observed within the SWS beam.

served with ISO to date. A temperature gradient is expected for warm gas in a variety of environments like PDRs (e.g. Sternberg & Dalgarno 1989, Burton, Hollenbach and Tielens 1990), shocks (Neufeld & Dalgarno 1989), and XDRs (e.g. Maloney, this volume).

NGC 1068 is however unusual in the strength of the S(0) transition, when compared to other galaxies (e.g. Rigopoulou et al. 1996, Valentijn et al. 1996). Interpreted as thermalized emission from a single temperature component, the S(0) and S(1) lines would correspond to about $1.5\times10^9 M_\odot$ of gas at about 100 K. Because of the steep temperature dependence of the rotational line emissivities (note that even the upper level of S(0) is 510 K above ground), it is however necessary to consider the effects of a distribution of temperatures. It should be noted here that the S(0) line effectively probes gas at temperatures in excess of about 50 K, so that the gas mass at lower temperatures is not constrained. Assuming a gaussian temperature distribution, we find that the observed line ratio matches e.g. a distribution of FHWM 50K, peaking at 85K, with about $3\times10^9 M_\odot$ total mass (Fig. 5). Of course, the inferred mass depends on the assumptions, but any plausible temperature distribution will require a gas mass that is at least a factor of $\sim$2 higher than for the idealized single temperature case. We have assumed that conversion between ortho and para molecular

hydrogen is fast enough to keep the ortho/para ratio in equilibrium at the local temperature. A fixed ortho-para ratio of 3 would again increase our mass estimate. Ortho/para considerations are, however, only significant at low temperatures as in NGC 1068, whereas at higher temperatures as in NGC 6946, for which Valentijn et al. 1996 inferred an ortho/para ratio of 3, the equilibrium ortho-para value will be close to 3 as well.

Such a large mass of warm gas comes close to the *total* gas mass inferred for the ISO beam from single dish (Planesas, Gómez-Gonzáles and Martín-Pintado 1989) and interferometric (Helfer & Blitz 1995) CO maps. This indicates unusually warm gas and/or that the standard CO to H_2 conversion factor is not applicable under the conditions near the nucleus of NGC 1068. The circumnuclear few arcseconds are known to be unusual e.g. by their high HCN/CO ratio (Sternberg, Genzel and Tacconi 1994). However, the interferometric CO observations yield nuclear H_2 masses less than $2\times10^8\,M_\odot$. On the other hand, ascribing the bulk of S(0) emission to an extended component or the star-forming arms would require these regions to be different from star-forming regions in starbursts which typically exhibit smaller S(0)/S(1).

Acknowledgements

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