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Letter to the Editor: first results from ISO

2.5 - 45μm SWS spectroscopy of the Circinus Galaxy*

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Abstract. We present 2.5-45μm ISO SWS spectra of the Circinus galaxy which is one of the closest spirals containing both a visually obscured Seyfert nucleus and circumnuclear starburst activity. In addition to PAH features, H_2 and low excitation ionic lines ([FeII], [NeII], [SIII]) from the starburst region its spectrum shows several prominent lines from highly ionized species ([NeIII,V,VI], [SIV], [MgV,VII,VIII], [OIV], [SiIX]) which arise in gas photoionized by the AGN within its ionization cone. Adopting solar abundances and a density of 5000 cm^{-3} derived from the [NeV]14.3/24.3μm ratio we have developed a model which can reproduce the absolute fluxes of most of the visible/near infrared and ISO lines from species with ionization energies in the range 50 - 320 eV to within a factor $\sim$ 2. Most of the discrepancies can probably be attributed to uncertainties in the calibration, abundances and atomic parameters. Of particular interest for further work are [OIV] 26μm and [SIV] 10.5μm which are observed to be a factor $\sim$ 2 brighter and fainter respectively than expected. The best fit ionizing spectrum is characterized by a $\nu^{-0.5}$ X-ray continuum - consistent with recent ASCA satellite observations - plus a pronounced *UV bump* which peaks at $\simeq$ 70eV (180Å) in a plot of νF_ν versus ν and is responsible for most of the ISO lines. Models in which the *UV bump* is represented by a broken power law, typical of a thin accretion disc, or a quasi black body at 2 x 10^5K give equally good fits to the observed emission line spectrum. Whatever its origin it appears that re-processed ionizing radiation from the AGN probably dominates over the starburst contribution to the total infrared luminosity.

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Key words: Infrared: galaxies – Galaxies: Seyfert – Galaxies: individual: Circinus – Line: formation

1. Introduction

The Circinus galaxy (A1409-65) is at a distance of only $\simeq$ 4 Mpc. It was included as a *template* galaxy within the SWS Central Programme because it is bright and exhibits narrow ($\simeq$ 150 km s^{-1}) high excitation visible and near infrared *coronal* lines (Oliva et al., 1994) plus a prominent [OIII] 5007Å ionization cone (Marconi et al., 1994) consistent with the presence of an AGN surrounded by an obscuring torus as proposed in the unified model of Seyfert galaxies. The prime aims of the ISO observations were to observe additional *high* excitation lines to improve detailed models of Circinus itself and to test the diagnostic use of these lines for investigating the luminosity sources in highly obscured programme galaxies e.g. the Ultraluminous Infrared Galaxies whose nature is still controversial. We used the Short Wavelength Spectrometer (SWS) described by de Graauw et al.(1996) on board the Infrared Space Observatory (ISO) satellite (Kessler et al., 1996).

2. Observations and results

Figure 1. is the complete spectrum obtained using SWS01 with an integration time per spectral element of only a few seconds. Figure 2. shows the 20 lines observed independently at higher s/n using the SWS02 spectral line scan mode. Line fluxes measured using the SWS interactive analysis system with the calibration tables valid as of 25.6.96 are given in Table 1. and are estimated to be accurate to $\simeq$ 30%. Those line fluxes measured independently using SWS01 and SWS02 generally agree to better than 30%. The 25μm continuum is higher but within

$\simeq$ 20% of that measured by IRAS. However, the [SiIX]3.93μm *coronal* line is 80% brighter than measured on the ground (Oliva et al., 1994) even though this line is believed to be confined to the nucleus so beam size effects should not be important. The spectra were obtained in apertures of 14x20, 14x27 and 20 x 33" which contain much of the star forming region as well as the nucleus. Particularly between 5 and 12μm the emission is dominated by PAH features and is remarkably similar to those of pure starburst galaxies observed with the SWS. The H_2S(1-7) lines also exhibit a similar dependence of column density versus excitation energy implying a large mass of molecular hydrogen at T $\simeq$ 250-800K in the starburst region. The ionic emission lines include [FeII](8eV), [NeII](22eV) and [SIII](23) which are dominated by the starburst; [SIV](35) and [NeIII](41) from potentially both the starburst and AGN (see model results below) and *higher* excitation [OIV](55eV), [NeV](97), [NeVI] (126), [MgV] (109), [MgVII] (187), [MgVIII] (225) and [SiIX] (303) lines from gas photoionized by the AGN.

Table 1. Ionic Line fluxes (10^{-20} W cm^{-2})

Species/$\lambda(\mu m)$	Flux [a]	Species	Flux[a]
[SiIX](2.59)	1.8	[SIV](10.54)	13(13.7)
[MgVIII](3.03)	6.5(6.9)	[NeII](12.8)	96(112)
[SiIX](3.93)	4.9(5.4)	[NeV](14.32)	44(34)
Brα(4.05)	3.9(6.1)	[NeIII](15.55)	44.3
[FeII](5.35)	6.2	[SIII](18.7)	35.7(49.9)
[MgVII](5.51)	6.9(5.5)	[NeV](24.31)	24.4(25.9)
[MgV](5.62)	5.1	[OIV](25.90)	72.3(83.6)
[ArII](6.99)	(31.6)	[FeII](26.0)	8.2(11.4)
[NeVI](7.66)	41.3(40)	[SIII](33.5)	134(113)
[ArIII](8.99)	9(7.1)	[SiII](34.86)	214(187)

[a] SWS02 with SWS01 values in parentheses

After allowing for the instrumental profile (FWHM $\simeq$115-280 km s^{-1}) the inferred linewidths are in the range 150-300 km s^{-1}. The high excitation lines are narrow for an AGN and generally narrower than the lower excitation ones although this is most probably an instrumental effect due to their smaller spatial extent. The prominent blue wing on the highest excitation [SiIX] line (303eV) is also visible in the groundbased spectrum and is attributed to the fact that this *coronal* line originates in outflowing gas within the ionization cone. Less pronounced blue wings are also visible in the profiles of other lines from high but not low excitation species.

3. Modelling of the AGN

3.1. Emission line spectrum and nuclear continuum.

Both the CLOUDY (Ferland, 1993; version c8406) and ION (Netzer, 1993) photoionization codes have been used to investigate the ionization structure of gas photoionized by the AGN with similar results. Line fluxes have been computed using R-matrix collision strengths for O, Ne, Mg and SIV and distorted wave approximations for the other species. Our primary aim was to infer the intrinsic spectral energy distribution and luminosity of the obscured central ionizing source. Constraints on the model include i) results based on visible and near-infrared *coronal* lines which favour photoionization over hot gas and imply a $\nu^{-0.5}$ spectrum around 300eV (Oliva et al., 1994) which is consistent with recent ASCA observations of a reflected X-ray component (Matt et al., 1996) ii) visible line ratios which imply a *UV bump* peaking around 70eV (180 Å) iii) Hα measured from a spatially resolved cloud within the ionization cone at $\simeq$ 10" from the nucleus which yields Ly$_c$ $\simeq$ $10^{53.3}$ photons s^{-1} for an intrinsically isotropic ionizing source and iv) a total covering factor of $\simeq$ 0.05 for the photoionized gas given by the ionization rate and *nuclear* Brα emission (or $\sim$ 0.5 if the emission is confined within the ionization cone).

The ISO spectra are of particular interest because i) most of the observed lines are from species with ionization energies of 50 - 300eV and therefore provide information on the AGN continuum in the region of the postulated *UV bump* and ii) the [NeV]14.3/24.3μm ratio provides a unique measure of the highly ionized gas density. A comment on the density derived from the [NeV] lines is in order in view of concerns about the collision strengths raised by the ratio 14.3μm/24.3 = 1.4 in the planetary nebula NGC6302 deduced from IRAS/KAO observations (Oliva, Pasquali and Reconditi, 1996). These now appear to have been resolved by a more accurate SWS measurement of 2.4 for this ratio in NGC6302 (D. Beintema, private communication) which is consistent with independent density estimates and the R-matrix [NeV] collision strengths computed including resonance effects. Its value of $\simeq$ 1.5 in Circinus (average of SWS01 and SWS02 results) clearly establishes that the density is lower than the 1.6 x 10^4 cm^{-3} determined independently in NGC6302 and yields a best estimate of $\simeq$ 5000 cm^{-3} for the high excitation gas.

The modelling presented here assumes solar abundances and the $\nu^{-0.5}$ X-ray spectrum; ionization rate; covering factor and density discussed above. Within these constraints the ISO line fluxes predicted for various ionizing spectra have been used to investigate the intrinsic spectrum of the obscured AGN continuum between $\sim$ 50 and 300eV. For any reasonable fit it is first of all clear that the ionizing continuum must steepen considerably at energies $\leq$ 250eV. Our more detailed conclusions concerning the continuum shape which yields the best overall fit to the line spectrum are illustrated in Figure 3. where it should be noted that the continuum is represented as νF_ν. The main result is the confirmation of the *UV bump*. In relation to its possible origin, however, we have found that virtually identical fits to the observed line spectrum can be obtained by adding a broken power law similar to that expected for an AGN accretion disc (Laor, 1990) or a $\simeq$ 2 x 10^5 K black-body to the $\nu^{-0.5}$ X-ray continuum. Both are shown on the plot and the broken power law is consistent with an α(ox) of -1.05 and is characterized by a slope of -0.5 except between $\simeq$ 95 and 250eV where it steepens to -3.5.

Figure 4. shows the ratio of observed to predicted ISO and related line fluxes up to an ionization potential of 330 eV. The values correspond to the model with the broken power law

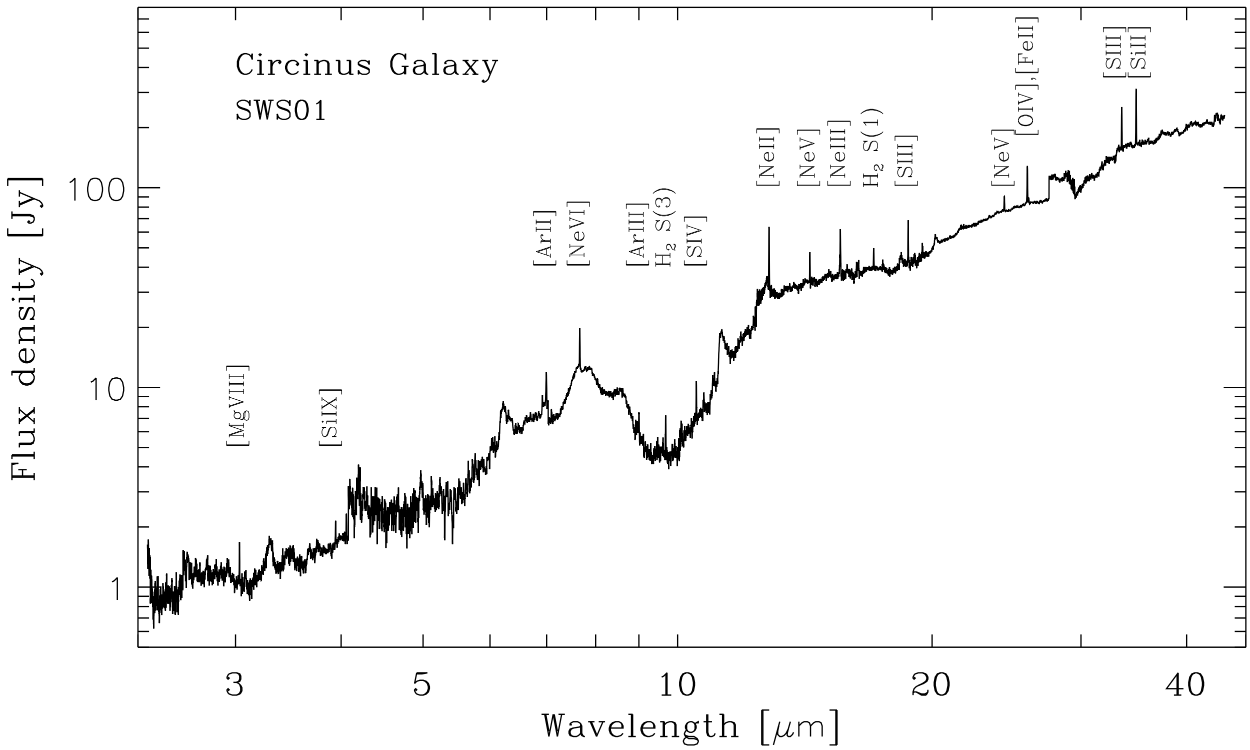

Fig. 1. 2.5 - 45μm spectrum of the Circinus galaxy obtained with SWS01.

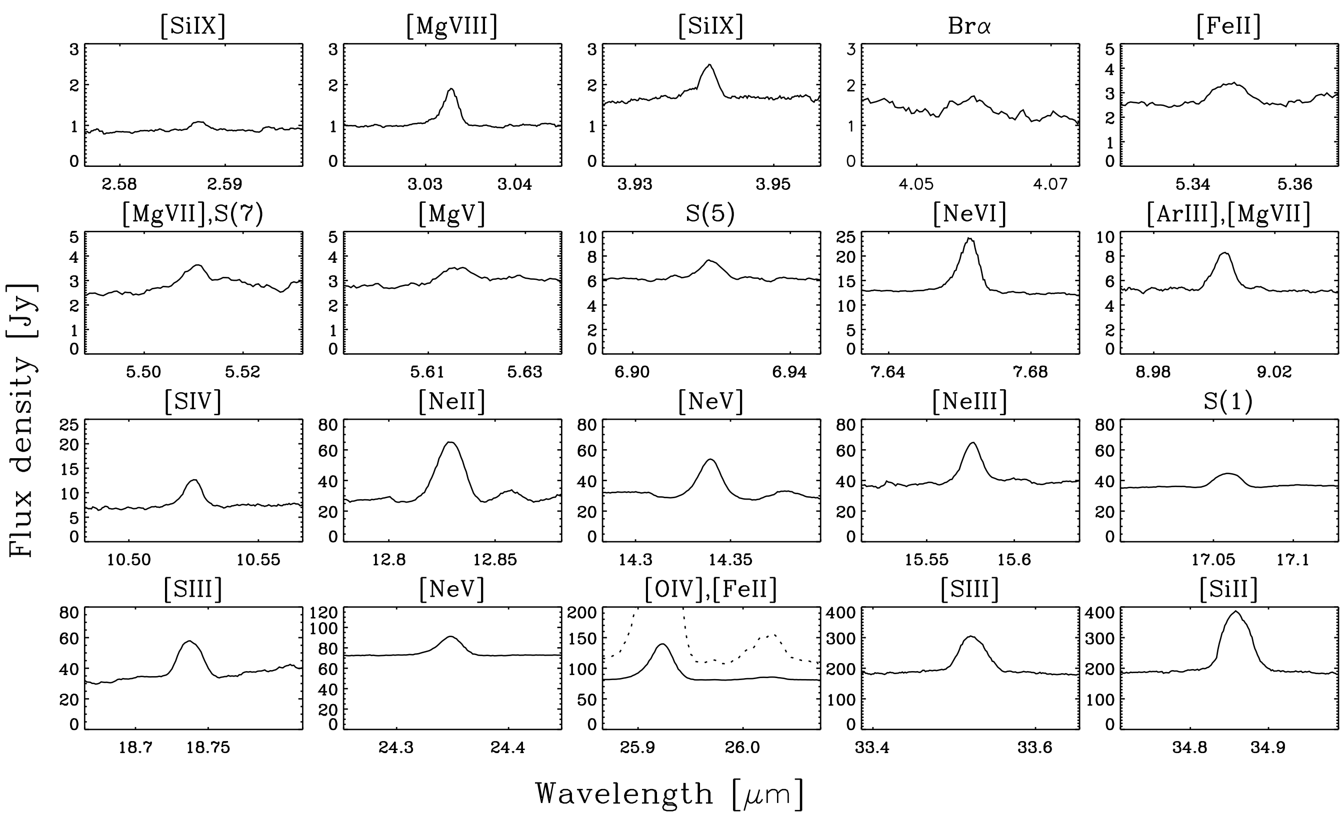

Fig. 2. Individual line scans with SWS02. Some structure in the spectra between 12 and 28μm e.g. [NeII], [NeV] is due to residual instrumental fringing effects. The spectrum around 26μm is also shown magnified by a factor 10 (dashed line) to show more clearly the [FeII] line which is separated from and much weaker than [OIV].

continuum but are virtually identical to those assuming a hot black-body. The ideal result, in which all points would be unity, has not been achieved but would also be suspicious in view of the various possible errors including calibration effects and uncertainties in the abundances and atomic parameters. For Si e.g. the discrepancies are smaller than the possible errors of $\sim$ 3 in the collision strengths while for [NeIII] the result could be used to imply that $\sim$ 50% of the flux originates in the starburst region.

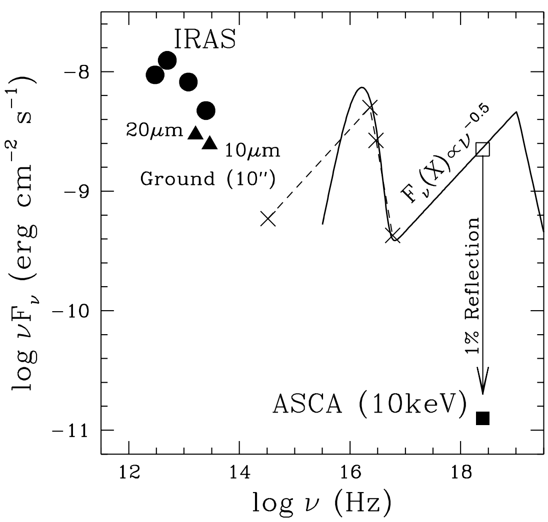

Fig. 3. Inferred ionizing spectrum together with the observed mid-far infrared continuum and reflected X-ray emission. The 10keV ASCA flux is consistent with the model assuming a 1% reflection efficiency.

At this stage it is therefore considered encouraging that most lines can be predicted within a factor $\sim$ 2. At the more detailed level, the most interesting discrepancies are probably those found for [OIV]26μm, which has been adopted as a prime AGN tracer, and the S lines. [OIV] has the highest observed flux relative to the model predictions whereas the S lines are too faint such that [OIV]/[SIV] is a factor $\sim$ 5 larger than expected which is difficult to explain - particularly as the ionization potentials are reasonably similar. These issues will certainly be re-addressed once more SWS spectra of other galaxies and galactic nebulae are obtained.

There is also no space here to re-discuss the other high excitation lines from elements not observed by ISO such as [FeVII,X,XI,X1V] included in Oliva et al., (1994). It is worth noting, however, that an HST image in the [FeXI]7892$\AA$ line could provide an additional test of our model. This was crudely estimated from groundbased imaging to arise in a region $\simeq$ 0.6" across, consistent with a density $\simeq$ 200 cm^{-3}, but is predicted to be confined within 0.2" if the higher density given by the [NeV] line ratio is correct.

3.2. Luminosities of the starburst and AGN.

Circinus has a total infrared luminosity estimated from IRAS data of $\simeq 10^{10} L_\odot$ of which, based on a decomposition of its spectral energy distribution, $\simeq$ 70% was attributed to the starburst by Rowan-Robinson and Crawford (1989). The maximum

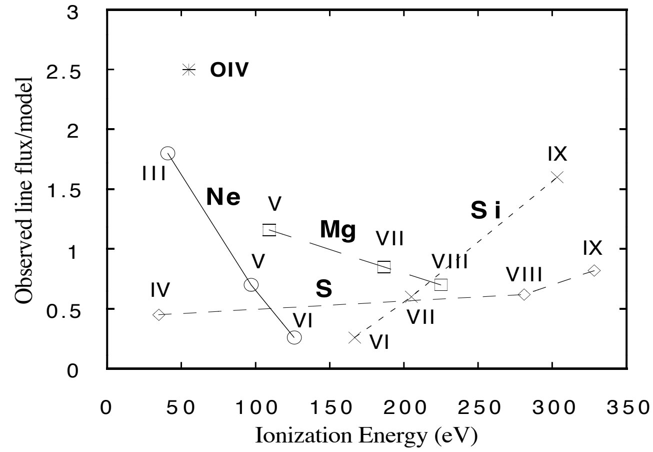

Fig. 4. Ratio of observed to model line fluxes for $Z_\odot$ and a broken power law continuum.

measured ISO Brα luminosity, however, is a factor $\simeq$ 15 lower than that of M82 in a similar aperture (Willner et al., 1977) and a groundbased Brγ map (Moorwood and Oliva, 1994) implies that about 50% of this originates in the nucleus. As M82 has an infrared luminosity $\simeq$ 3 x $10^{10} L_\odot$ and as its ratio of recombination line to infrared luminosities is typical for starbursts, the starburst luminosity in Circinus may only be $\simeq 10^9 L_\odot$ or $\simeq$ 10% of the total. The AGN luminosity can be derived by integrating under the spectral energy distribution in Figure 3. Assuming that the radiation is intrinsically isotropic leads to an estimate of $\sim$ 5 x $10^9 L_\odot$ for the emission in the *UV bump* alone which is likely to be reprocessed into far infrared emission. The X-ray luminosity is comparable although a smaller fraction may be absorbed by dust. It appears therefore that the AGN dominates over the starburst and may contribute up to $\sim$ 90% of the total luminosity.

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