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ISO-SWS spectroscopy of Arp 220: a highly obscured starburst galaxy*

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Abstract. We report the first 2.4 - 45μm spectroscopic study of Arp 220 obtained with the Short Wavelength Spectrometer onboard ISO. Observations of mid infrared lines penetrate deep into the highly obscured regions where the luminosity originates and give direct clues to their sources of excitation. From the observed Brackett line ratios and from the [S III] 18.7μm/33.5μm line ratio we derive a mean extinction of $A_V \approx 50$ mag, significantly higher than most earlier values. No AGN indicators such as the high excitation [Ne V] or [O IV] lines are detected to an upper limit significantly less than in bona fide AGN galaxies, indicating that a central AGN could only be a minor contributor to the total luminosity. The intensities of the low excitation [Ne II] and [S III] lines, and the extinction corrected ratio of the Lyman continuum and bolometric luminosity imply that massive star-formation is the dominant source of luminosity in Arp 220. The spectra include bright emission of the pure rotational S(1) and S(5) lines of molecular hydrogen. If the extinction to the emitting region is the same as to the ionized medium, as much as 10% of the ISM of Arp 220 could be in the warm phase sampled by these lines.

Key words: galaxies: individual: Arp 220 – infrared: galaxies

1. Introduction

Arp 220 (= IC 4553) is the nearest (77 Mpc for H_0 = 75 km/s/Mpc) and well studied example of an ultraluminous infrared galaxy (ULIRG). The discovery of this class of galaxies with enormous infrared luminosities of $L_{IR} \geq 10^{12} L_\odot$ (cf. Sanders et al. 1988) was one of the major results of the IRAS mission. ULIRGs are widely believed to be the result of recent or ongoing merging of two gas-rich galaxies (see e.g. Sanders et al. 1988). Nevertheless the basic question related to Arp 220 (and ULIRGs in general) is still not answered: what is the source of the extreme infrared luminosity? The mechanisms proposed as energy source are powerful starbursts (e.g. Shaya et al. 1994), active galactic nuclei (AGNs) (e.g. Graham et al. 1990) and kinetic energy of colliding galaxies (e.g. Harwit et al. 1986). Sanders et al. 1988 suggested an evolutionary sequence merger-starburst-AGN. In this scenario tidally induced gas flows into the galactic nuclear regions generate bursts of star formation and fuel an existing or newly created AGN.

In fact there is evidence for both ongoing starbursts and Seyfert nuclei in Arp 220: Strong stellar CO absorption bands (Armus et al. 1995), a huge concentration of molecular gas in the core ($M(H_2 + He) \approx 2.5 \cdot 10^{10}\ M_\odot$ - Scoville et al. 1991), strong PAH features (Rieke et al. 1985) and near infrared colours similar to dusty starburst galaxies (Mazzarella et al. 1992) are some of the indications for rapid star formations. Shaya et al. 1994 have found massive young star associations that might contribute about 10% to the luminosity. On the other hand there is also evidence for a dust enshrouded, optically hidden central AGN, derived for instance from the LINER like optical spectrum (Rieke et al. 1985), the broad Brα line (FWHM $\approx$ 1300 km/s) reported by DePoy et al. 1987, and the difficulty to reconcile the ratio of inferred Lyman continuum luminosity to bolometric luminosity with starburst models (see e.g. DePoy et al. 1987).

The total extinction toward the obscured energy source(s) in Arp 220 cannot be reliably derived from optical or even near-infrared measurements, making it difficult to quantify possible starburst or AGN contributions to the total luminosity.

ISO overcomes several of the problems that hamper the study of ULIRGs. The dust extinction is significantly lower than in optical and near-infrared regions. Fine structure lines

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Table 1. Fluxes (and upper limits) of selected emission lines

Identification	λ_0 [μm]	Measured [W/cm^2]	Corrected[a] [W/cm^2]
Brβ	2.625	3.8e-21	3.3e-19
Brα	4.052	2.1e-20	2.4e-19
H_2 S(5)	6.910	2.4e-20	2.4e-19
H_2 S(2)	12.279	<1.5e-20	<7.0e-20
[Ne II]	12.814	5.2e-20	2.2e-19
[Ne V]	14.320	<4.1e-21	<1.0e-20
H_2 S(1)	17.035	2.3e-20	9.7e-20
[S III]	18.713	<2.0e-20	<9.3e-20
[O IV]	25.89	<5.0e-21	<1.2e-20
H_2 S(0)	28.219	<3.5e-20	<7.3e-20
[S III]	33.480	1.3e-19	2.2e-20
[Si II]	34.814	9.7e-20	1.6e-19

[a] extinction corrected for A_V = 50 mag

from ions in various ionization stages can be used to examine the physical conditions and to distinguish between starburst and AGNs. In this letter we report the first spectroscopic study of Arp 220 in the ISO-SWS range.

2. Observations and Results

Spectra of Arp 220 have been obtained with the Short Wavelength Spectrometer (SWS) onboard ISO on Januar 24 and March 6, 1996. In total 23 spectral lines have been measured in the range between 2.6 and 37 μm in the grating line scan mode (AOT SWS02). Arp 220 can be considered a pointsource for SWS, implying spectral resolution between 1000 and 2500 (De Graauw et al. 1996). No aperture corrections to the fluxes are required. The spectra have been reduced using the SWS Interactive Analysis system (IA), in combination with additional tools to improve various steps of the reduction such as dark current subtraction or flat fielding.

We carried out observations at the wavelengths of the following spectral lines: the hydrogen recombination lines Brα, Brβ, and Pfα, the molecular hydrogen lines H_2 S(5) 6.9μm, S(2) 12.3μm, S(1) 17.0μm, and S(0) 28.2μm, the fine structure lines of [FeI] 24.0μm, [FeII] 26.0μm, [FeIII] 22.9μm ,[MgV] 5.6μm, [NeII] 12.8μm, [NeIII] 15.6 and 36.0μm, [NeV] 14.3 and 24.3μm, [Ne VI] 7.6μm, [OIV] 25.9μm, [SI] 25.2μm, [SIII] 18.7 and 33.4μm and [SiII] 34.8μm. From this set of 22 lines a total of only 7 emission lines were detected. They are shown in Fig. 1, together with [SIII] 18μm and [OIV] 26μm to demonstrate the upper limits. The measured line fluxes as well as upper limits for some of the not detected lines are summarized in Table 1. The upper limits were derived from gaussian profiles of width equal to other lines of the same (or comparable) species, scaled to a peak height corresponding to approximately 3σ of the noise.

The Brackett lines appear double peaked with a separation of $\Delta v \approx 300...400 km/s$. This is consistent with the results for Paβ and Brγ of Larkin et al. 1995. DePoy et al. 1987 reported a FWHM of at least 1300 km/s, interpreted as evidence for an AGN. Our double-peaked line profile, interpreted as a single line as it would appear at lower resolution, would yield a FWHM close to 1000 km/s. The double peaked profile however is much more naturally explained as being due to shifted emission from the two nuclei, rather than an AGN broad line.

3. Discussion

3.1. Extinction

The small line to continuum ratios of fine structure lines that are strong in other galaxies we have observed with ISO-SWS (Rigopoulou et al. 1996, Moorwood et al. 1996, Kunze et al. 1996) immediately suggest that in Arp 220 the extinction is large even in the near- and mid-infrared. It is known from previous studies that the inferred extinction increases rapidly with the wavelength of the extinction diagnostics. For example the Hα/Brγ line ratio yields a (screen) extinction of $A_V \approx 7$ mag (Rieke et al. 1985), whereas Larkin et al. 1995 derived values of A_V = 10 and 13 mag for the two nuclei from measurements of the Paβ/Brγ ratio. From the slope of the continuum between 3.2 and 3.6 μm Rieke et al. 1985 found A_V = 15...20. Smith et al. 1989 estimated $A_V \approx 90$ mag from the 9.7μm silicate absorption. Most previous studies of Arp 220 have adopted an average extinction of $A_V \approx 10$ mag.

With the ISO measurements we are for the first time able to directly measure the extinction at wavelengths that penetrate much deeper into the regions where the luminosity originates. Values derived from the comparison of the observed line ratios to their intrinsic ratios are given in Tab. 2. For $\lambda < 7\mu$m we used the extinction law of Rieke, Rieke and Paul (1989). For $\lambda > 7\mu$m we used the law given by Draine (1989). in Table 2 we list the foreground (screen) extinctions inferred from the Brackett line ratios and the [S III] 18.7μm/33.5μm line ratio. We adopted intrinsic ratios for the hydrogen recombination lines assuming case B conditions and an electron temperature of 10000 K (Hummer & Storey 1987). In our analysis we used the Brγ flux of 5.9 $\cdot 10^{-22}$ W/cm^2 measured by Goldader et al. (1995). The intrinsic [S III] 18.7μm/33.5μm line ratio is insensitive to the gas temperature and is ≈ 0.5 in the limit of low electron density ($n < 100 cm^{-3}$). The ratio increases with increasing gas density, so our observed ratio of <0.15 yields a foreground extinction of at least A_V = 59 mags.

In optical/near-infrared studies it is often found that a simple foreground screen model for dust extinction does not properly describe the situation in infrared galaxies and that models in which the emitting sources are mixed with the dust fit the observations better. However, the ISO line ratios cannot be reproduced by a mixed model even in the high optical depth limit ($\tau_V \rightarrow \infty$). This suggests that in Arp 220 the *mid-infrared* lines may actually probe a central region which is largely obscured by foreground material.

Since the Brackett lines are double peaked and weak it is difficult to derive reliable estimates for A_V from these lines. The

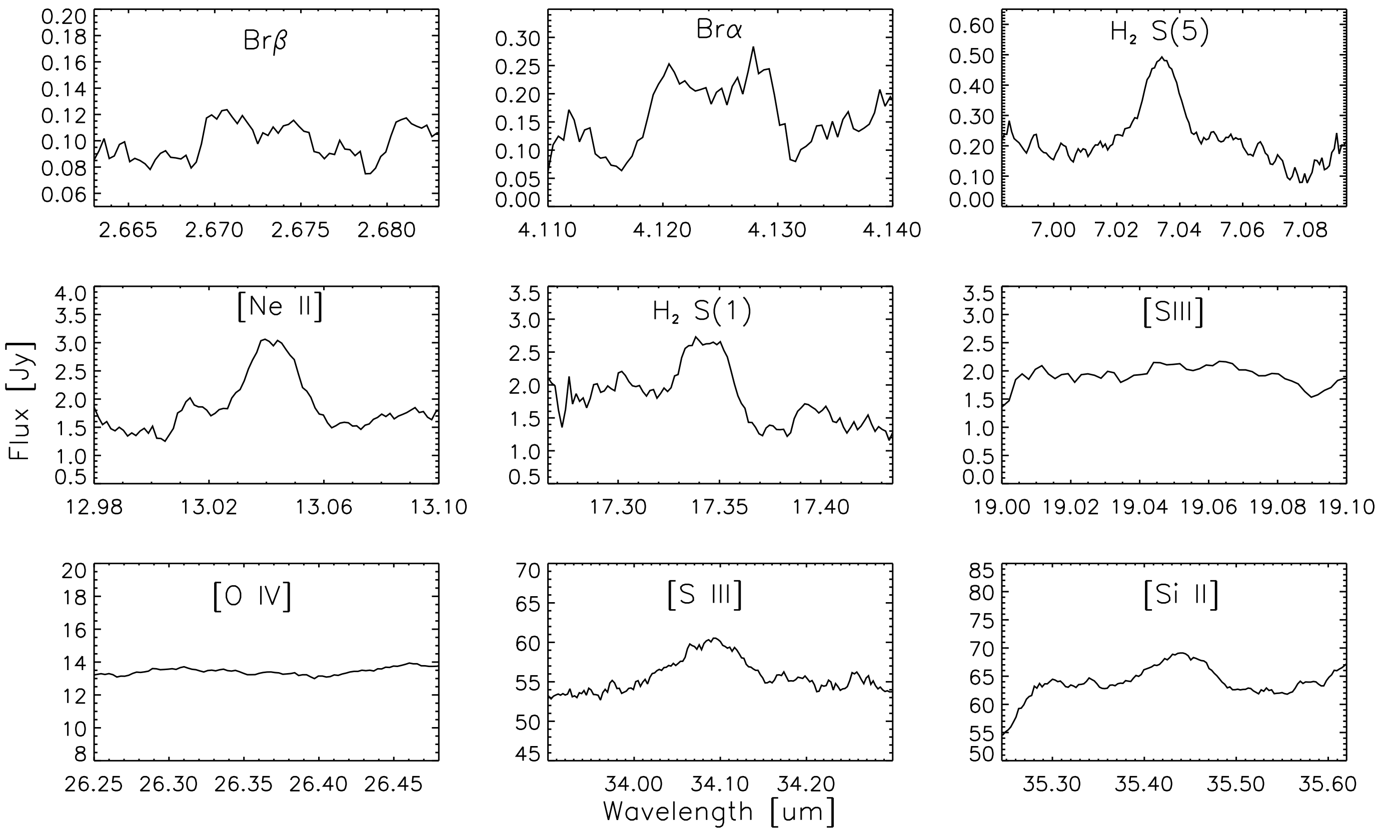

Fig. 1. The spectra of Arp 220. The steep flux decrease on the left side of the [Si II] line is due to a strong 34.6μm OH $^2\Pi_{3/2}, J = 3/2 \rightarrow {}^2\Pi_{1/2}, J = 5/2$ absorption feature, which has been measured separately and will be discussed elsewhere (Skinner et al., in preparation)

Table 2. Values for A_V derived from observed line ratios for a screen model

ratio	A_V [mag]	ratio	A_V [mag]
Brα/Brβ	30	Brβ/Brγ	83
Brα/Brγ[a]	56	SIII 18/SIII 33	≥59

[a] Br_γ from Goldader et al. 1995

most reliable estimate therefore arises from the upper limit of the [S III] ratio, and we henceforth assume a mean value of A_V = 50± 10 mag. Very high extinction is also inferred from the 9.7μm silicate absorption (Smith et al. 1989, $A_V \approx 90$ mag) and is consistent with the observed infrared colours (Mazzarella et al. 1992). Significantly lower values have however been adopted by most past studies of Arp 220.

3.2. Warm molecular hydrogen

For the first time, pure rotational transitions of molecular hydrogen, like the S(5) 6.91 μm and S(1) 17.04 μm lines detected in Arp 220, allow to probe directly the warm (few 100 K) molecular phase of the interstellar medium in external galaxies. The extinction-corrected S(1) flux of $\approx 1 \cdot 10^{-19}$ W/cm^2 is close to the fluxes of the brightest fine structure lines, indicating the importance of the warm molecular medium in Arp 220. The S(1) line may be collisionally excited in warm gas heated by shocks or UV photons associated with the on-going star-formation.

It is likely that the S(5) line arises in regions which are considerably warmer than the gas in which most of the S(1) line emission is produced (c.f. Rigopoulou et al. 1996). From the dereddened upper limits we can place on the fluxes of the S(0) and S(2) lines we infer that the S(1) emission is probably produced in gas at temperatures between 100 and 500 K. If we adopt a temperature of 150 K, consistent with SWS observations of NGC 3256, Circinus, or NGC 4038/39 (Rigopoulou et al. 1996, Moorwood et al. 1996, Kunze et al. 1996) the S(1) line flux implies a 'warm' molecular hydrogen mass of $3.5 \cdot 10^9$ M$_\odot$. This mass corresponds to about 10% of the total molecular mass of $3.5 \cdot 10^{10}$ M$_\odot$ inferred from CO 1-0 rotational line measurements (Scoville et al. 1991).

This estimate is however subject to considerable uncertainty due to the adopted temperature and the possibility that at least the regions dominating the near-infrared rovibrational H_2 emission might be subject to less extinction than the nuclei (Goldader et al. 1995).

3.3. AGN or Starburst?

The ionic fine structure lines observable with SWS offer a unique opportunity to discriminate between starbursts or AGNs as the main source of luminosity of highly obscured galaxies. Ionization by the soft stellar continuum in star forming regions creates bright low excitation lines like [Ne II] 12.8μm, [Ne III] 15.6μm, [S III] 18.7, 33.5μm, while high excitation lines are absent ([Ne V] 14.3, 24.3μm) or very faint ([O IV] 26μm). In contrast, ionization by AGN continua extending to much higher energies, maintains significant emission in low excitation lines, but creates strong high excitation AGN indicators like [O IV], [Ne V] or [Ne VI] 7.6μm. This is empirically confirmed by the first SWS observations of bona fide starburst and Seyfert galaxies (Rigopoulou et al. 1996, Kunze et al. 1996, Moorwood et al. 1996) and is well understood from photoionization models.

In Arp 220 we did not detect the high excitation fine structure lines of [O IV], [Ne V], and [Ne VI] which require much harder radiation fields than can be produced in a starburst. The extinction-corrected 3σ limits on the diagnostic line ratios [O IV] 26μm / [Ne II] 12.8μm < 0.055 and [Ne V] 14.3μm / [Ne II] 12.8μm < 0.045 are well below the ranges 0.3. . .0.9 and 0.15. . .0.8 observed with ISO in AGNs. While these limits clearly cannot exclude the presence of a low luminosity AGN, they are evidence that Arp 220 is primarily powered by star formation.

An important check on the starburst model is to establish that the starburst can indeed account for the total luminosity, i.e. that the starburst-dominated region is not just foreground, while the source of the major part of the luminosity remains unconstrained. To this purpose, we compared both Lyman continuum fluxes (L_{Lyc}) deduced from extinction-corrected Brackett lines and the extinction-corrected [Ne II] flux to the bolometric (far-infrared) luminosity (L_{Bol}). The Arp 220 values are within factors 0.7. . .5 from those for starburst galaxies like M 82, NGC 4038/39, NGC 4945, NGC 5253 and NGC 3256, that means within plausible scatter of starburst properties (see Lutz et al. 1996 for tabulated values). Averaging the L_{Lyc} values obtained from the [Ne II] luminosity (scaled with a factor of 60, which is determined on starburst galaxies) and from the Brackett lines we deduce $L_{Bol}/L_{Lyc} \approx 20$, which can easily be fit by starburst models. Our conclusion that *Arp 220 is powered by massive stars formed in a recent starburst* differs from previous analyses of Arp 220 because of the significantly higher extinction found from ISO spectroscopy, and because of the ability to put upper limits on AGN tracing high excitation lines.

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