IMPLICATIONS OF THE ISO LWS SPECTRUM OF THE PROTOTYPICAL ULTRALUMINOUS GALAXY: ARP 220*

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ABSTRACT

We present a low resolution ($R = \lambda / \Delta\lambda \sim 200$) far-infrared (43-197 μm) spectrum of the ultraluminous galaxy Arp 220, obtained from deep full-range scans using the Long Wavelength Spectrometer (LWS) aboard the Infrared Space Observatory (ISO). The spectrum is vastly different from the spectra of less luminous IR bright galaxies: the fine-structure lines that are typical of IR bright galaxies are weak or absent and the spectrum is dominated by absorption lines of OH, H_2O, CH, NH_3 and [O I]. From the 43-197 μm continuum fit we derive that the optical depth of the thermal dust emission, τ_{dust}, is about unity at 150 μm. From our continuum fit we derive a Lyman continuum production rate of $Q = 9 \times 10^{54}$ sec^{-1} and our simple spherical radiative transfer solution indicates a cool central source. The upper limits on the FIR fine-structure lines indicate a softer radiation field in Arp 220 than in starburst galaxies such as M82 or in AGN. The low $L_{[CII]\ 158} / L_{FIR}$ ratio in Arp 220 cannot be easily explained by dust obscuration or saturation effects. These results may be explained by a starburst model with a low upper mass cutoff or by unusually high dust absorption of UV photons within the ionized regions of a starburst or AGN.

Keywords: active galaxies; infrared spectroscopy.

1. INTRODUCTION

As the closest (77 Mpc, $H_o = 75$ km s^{-1}) and brightest of the class of ultraluminous infrared galaxies (ULIGs), Arp 220 ($L_{IR} \sim 1.5 \times 10^{12}\ L_\odot$) is often considered to be the prototype of its class. As is typical for galaxies in this class, Arp 220 is in the final stages of the merging of two galaxies. Whether or not Arp 220 contains a luminous active galactic nucleus that powers most of its infrared luminosity, is a question hotly debated and important for our understanding of the evolution of galaxies and of the origin of active galactic nuclei. We try to answer this question by probing the hardness of the radiation field using diagnostic mid- and far-infrared fine-structure lines. Both the detection/non-detection of the presence of an active galactic nucleus (or a young starburst) and the derivation of the total luminosity of these sources can be highly sensitive to extinction. For example, if the obscuring dust is mixed with the emitting gas, foreground sources may dominate short wavelength observations while the source responsible for powering most of the emission can be effectively hidden. Thus, to understand the energetics of a galaxy as highly obscured as Arp 220, far-infrared spectroscopy is of critical importance.

2. THE OBSERVATIONS

As part of the LWS consortium "Central Program" study of infrared-bright galaxies, the observations of Arp 220 and other bright program galaxies were designed to achieve sufficient signal-to-noise to detect a set of seven diagnostic far-infrared fine-structure lines, assuming line-to-continuum ratios similar to those seen in the nearby starburst galaxy M82 (Lord et al. 1996): the [O III] 52 and 88 μm, [N III] 57 μm, [N II] 122 μm, [O I] 63 and 146 μm, and [C II] 158 μm lines. Over 13,000 seconds of ISO observing time was devoted to obtaining a deep, full range ISO LWS 43 – 197 μm,

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low resolution ($R = \lambda/\Delta\lambda \sim 200$) spectrum of Arp 220. The LWS aperture size is ~ 70", encompassing all of the far-infrared flux of Arp 220 (Clegg et al. 1996; Swinyard et al. 1996).

The data were deglitched and calibrated with the ISO LWS Pipeline 5. The ISO Spectral Analysis Package (ISAP) was used to further deglitch and coadd the data. The beginning and ending data within each detector scan were found to be less reliable than the central regions of the scan. However, because of the redundancy from neighboring detectors, these data could be omitted still leaving sufficient overlapping data to be used for scaling factors of $\leq 25\%$, our estimated calibration error, to produce a continuous spectrum.

The full LWS spectrum of Arp 220 is shown in Figure 1. Although the expected signal-to-noise was achieved, with the exception of weak [C II] emission, no fine-structure lines were detected in emission. Instead, the spectrum is dominated by absorption lines of OH, H_2O, CH, NH_3, and [O I] and other (as yet) unidentified lines. For example, six absorption lines and one emission line from the $^2\Pi_{3/2}$, $^2\Pi_{1/2}$, and cross-rotational ladders of OH and thirteen absorption lines of H_20, from lower energy levels up to 300 cm^{-1}, were detected. The spectrum is markedly different from other IR bright, less luminous starburst galaxies in our survey, such as M 82, NGC 253, NGC 6240, and NGC 3690, whose far-infrared spectra are dominated by strong forbidden fine-structure line emission, but similar to that of the ULIG Mkn 231. Here we present the current status of analysis of the continuum and fine-structure lines. Detailed analysis of the molecular lines will be discussed in a future paper.

3. THE DUST OPTICAL DEPTH AND THE CENTRAL SOURCE TEMPERATURE

To estimate the dust optical depth, $\tau_{dust}(\lambda)$, we fit the LWS far-infrared continuum spectrum with a function of the form

$$F_\lambda \propto B_\lambda(T)(1 - e^{-\tau_{dust}(\lambda)})$$

assuming constant dust temperature and $\tau_{dust}(\lambda) = (\lambda_o/\lambda)^\alpha$ where $\alpha = 1 - 2$, and λ_o is the wavelength where $\tau_{dust} = 1$. The best fit, shown in Figure 2, was obtained with $\alpha = 1.75$, $T = 56$ K, and $\lambda_o = 150$ µm. More realistically, we fit the data with a central source + dust shell radiative transfer model using a silicate (53%) and graphite (47%) grain mixture (Draine and Lee 1984) and allowing temperature and density ($n \propto r^{-1.5}$) variation. We obtained a good fit using two cool central source temperatures (T_1= 5900 K and T_2=115 K), inner and outer radii of 40 and 200 pc and dust temperatures of 250 and 50 K, respectively. We show the dust

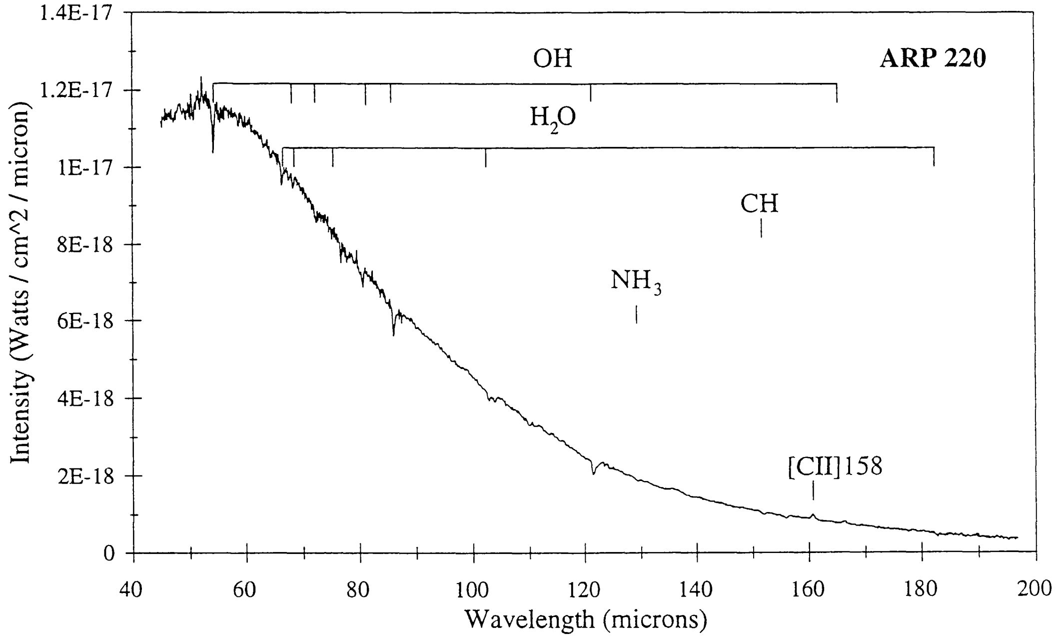

Figure 1. The ISO LWS spectrum of Arp 220. The positions of the strongest lines are indicated.

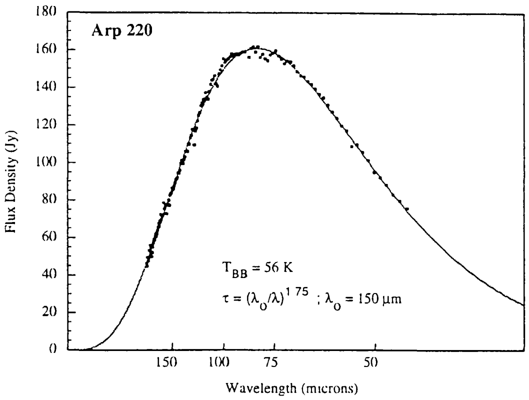

Figure 2. Best single temperature fit to the Arp 220 continuum.

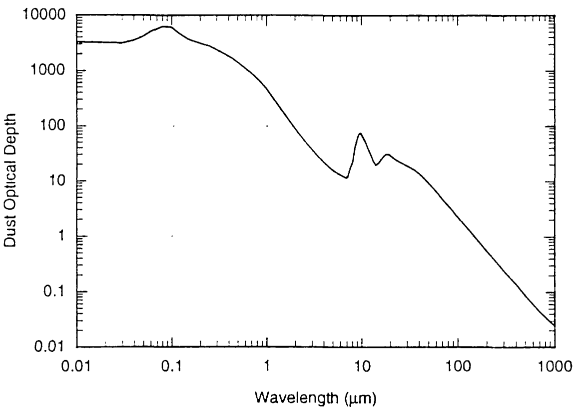

Figure 3. Dust optical depth as a function of wavelength in Arp 220 based on a spherical dust shell + central blackbody model (see text).

optical depth as a function of wavelength for this model in Figure 3. Important for models of the molecular absorption, is the fact that the dust temperature at $\tau_{dust}(\lambda) \sim 2/3$ varies from $T_{2/3}(180\ \mu\text{m}) \sim 220$ K to $T_{2/3}(20\ \mu\text{m}) \sim 60$ K. The high values of $\tau_{dust}(\lambda)$ we derive are consistent with the high column densities of gas derived from millimeter observations of CO (Scoville et al. 1997). Any source embedded deep within such a dust shell may well be hidden from view even at mid-infrared wavelengths.

4. THE LYMAN CONTINUUM RATE AND THE HARDNESS OF THE RADIATION FIELD

To estimate the Lyman continuum production rate, we extrapolated our thermal dust continuum fit to 2.7 mm. Subtracting thermal dust and non-thermal radio (Norris 1988) extrapolated components from the 2.7 mm continuum flux (Scoville et al. 1991), we derive a residual flux of 12.6 mJy. Under the assumption that the residual is due to optically thin free-free emission, we estimate a Lyman continuum production rate of $Q = 8.9 \times 10^{54}\ s^{-1}$. Comparing this to the Brα line flux measured with the ISO SWS (Sturm et al. 1996) would imply an extinction *to the starburst* of $A_v = 24$ (assuming α=1.75) and considerably less dust along the line of sight than implied by the optical depth we derive for the entire column of dust (see Figure 3). This could be because the starbursts (at least those we detect in Brα) really do lie toward the outer regions of the dusty nuclear regions or because of the effects of scattering at Brα, which we have not taken into account.

To probe the hardness of the radiation field of the ionizing source, our upper limit on the [O III] 52 μm (E_p=35 eV) line ($\leq 7 \times 10^{-20}$ W cm^{-2}, 3σ) can be compared with the observed flux in the [S III] 34 μm (E_p=23 eV) line (Sturm et al. 1996), assuming solar abundances. These lines have nearly identical critical densities ($n_{crit} \sim 5 \times 10^3$ cm^{-3}) and this line flux ratio is relatively insensitive to the extinction. While in M82, Lord et al. (1996) observe [S III]34 μm / [O III]52 μm = 1.35, the ISO observations of Arp 220 yield an observed ratio of > 2 (3σ). Higher extinction in Arp 220 makes this difference more pronounced. These results would appear to rule out an AGN as the predominant energy source for the FIR luminosity in Arp 220 or, if a starburst powers the FIR emission, they imply that it must be older or have a lower upper mass cutoff than in M82 (unless the central source is hidden even at 52 μm or if dust in the ionized region softens the spectrum).

6. STARBURST MODELS

To derive the parameters of the starburst, an evolutionary synthesis code (Leitherer & Heckman 1995) was used to compute the starburst spectral energy distribution for input to CLOUDY (Ferland 1993). For an instantaneous burst with solar abundances and a Salpeter IMF (α=-2.35) for masses 1 - 100 M_o, we used the model [SIII]34 μm /[OIII]52 μm line ratio as a function of age to date the starburst using a radius of 235 pc (Scoville et al. 1997). Using the "Orion HII region model" in CLOUDY, and assuming that the starburst powers the FIR, a starburst age of $> 8 \times 10^6$ years and $n_e = 500$ cm^{-3} are consistent with the observed line ratio and line fluxes, but the Lyman continuum flux is a factor of 3 lower than our derived value. Models with unusually large dust-to-gas ratios may allow a better fit to the observations (Satyapal et al. 1998).

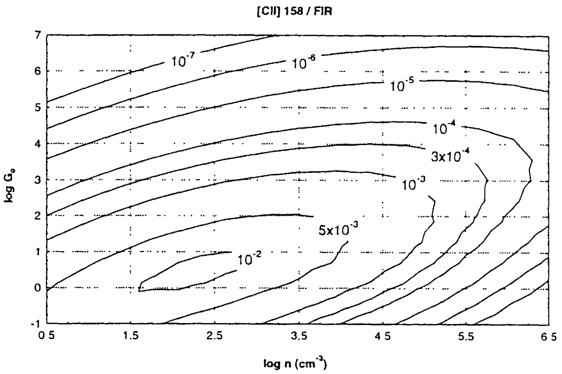

Figure 4a. Contour plot of $L_{[C\ II]158} / L_{FIR}$ as a function of G_o and n(cm^{-3}) with Orion-type abundances based on the models of Kaufman, Wolfire & Luhman (1998). For Arp 220, this ratio is 10^{-4}.

7. PHOTODISSOCIATION REGION MODELS

As in other ULIGs (Luhman et al. 1998), $L_{[C\ II]158} / L_{FIR}$ is lower by a factor ~ 10 in Arp 220 relative to typical starburst galaxies. Since the [O I] 63 μm line is self-absorbed, we use our upper limit on the [O I] 145 μm line emission to compare with PDR models to try to deduce the average incident far-ultraviolet radiation field flux G_o (in units of the local interstellar radiation field) and PDR gas density n(cm^{-3}). Figure 4 displays $L_{[C\ II]158\ \mu m} / L_{FIR}$ and $F_{[C\ II]158\mu m} / F_{[O\ III]145\mu m}$ as a function of n and G_o as predicted by Kaufman, Wolfire & Luhman (1998) in their recent models including the effects of PAH heating. These models also include the effects of saturation of the [C II] line at high n and/or G_o (Luhman et al. 1998). Based on our [C II] 158 μm and [O I] 145 μm line flux measurements of 8.7 ± 0.04 and ≤ 1 (3 σ) $\times 10^{-20}$ W cm^{-2} these ratios are 10^{-4} and ≥ 10 respectively in Arp 220. Even if the [O I] 145 μm line flux is just below our detection limit, from which we would derive $G_o \sim 20$ and $n_{PDR} \sim 3 \times 10^5$ cm^{-3}, the derived value of G_o is unusually low for both galactic star forming regions and starburst galaxies. It does not appear that the low [C II] line flux is due to extinction by dust at 158 μm, given our derived A_v to the starburst and even the total dust extinction through the cloud (see §3). Self-absorption in the [C II] line is a possible explanation which we are exploring with follow-up LWS Fabry-Perot observations ($R = \lambda / \Delta\lambda \sim 10^4$). Alternatively, the low [C II] line flux could indicate a stellar population deficient in massive main sequence stars, due either to age or to a low upper mass cutoff (see Satyapal et al. 1998).

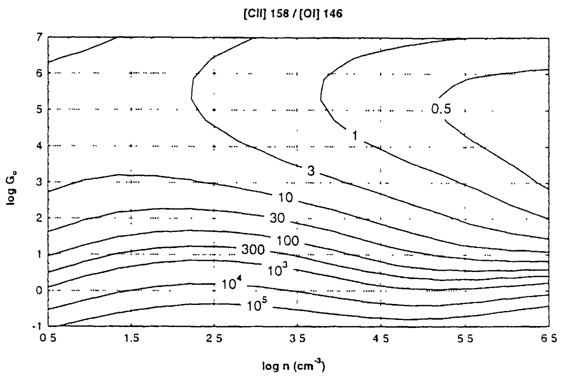

Figure 4b. Contour plot of $F_{[C\ II]158\mu m} / F_{[O\ III]145\mu m}$ as in Figure 4a. For Arp 220, this ratio is ≥ 10.

8. SUMMARY

We have analysed the shape of the far-infrared continuum and the weakness of the far-infrared fine-structure lines in Arp 220. Based on a spherically symmetric model we find that the far-infrared emission comes from a region extending radially from 40 - 200 pc with $\tau_{dust}(150\ \mu m) \sim 1$. We derive a Lyman continuum rate $Q \sim 9 \times 10^{54}$ s^{-1} and extinction to the starburst of $A_v = 24$. The upper limits on the FIR fine-structure lines indicate a softer radiation field in Arp 220 than in starburst galaxies such as M82 or in AGN. These results cannot be easily explained by dust obscuration, but may be explained by an older starburst, one with a low upper mass cutoff, or by unusually high dust absorption of UV photons within the ionized regions of a starburst or AGN.

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Question from Pierre Cox

Question: In the case of SgrB2, LWS Fabry-Perot measurements show that the [C II] 158 μm line is seen in absorption. It is thus very likely that this will also occur in Arp 220.

Answer: We will soon know the answer.

Question from Dieter Lutz

Question: Is the relatively small G obtained from the PDR analysis still consistent with the lower limit one should be able to obtain from the luminosity and size of the Arp 220 starburst?

Answer: G obtained in this manner is on the order of 10^5, in contrast to the small G obtained by comparison of the [C II] 158μm and [O I] 145 μm line observations to the models. We do not think these lines are greatly affected by extinction to the PDR regions, considering the extinction we have derived to the HII regions. Perhaps these line fluxes are affected by self-absorption. We have obtained follow-up Fabry-Perot observations looking for self-absorption in the [C II] 158 μm line in Arp 220. On the other hand, playing devil's advocate, we note that G can be smaller than derived from this approximation if the PDRs are located around individual Stromgren spheres, and not around a starburst wind, or if the radiation field is softer than typical of O/B stars, as we have inferred from our data.