Megamaser Physics Revealed by the Starburst Galaxy Arp 220[1]

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[1]Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

Ultra-Luminous InfraRed Galaxies are a class of galaxies with very large far-infrared luminosities whose power source is controversial. In one theory[1] a quasar-like Active Galactic Nucleus is surounded by a dense dust torus which absorbs the powerful nuclear emission, is warmed and re-emits at far-infrared wavelengths, and hides the nucleus from direct view. In another[2], in dense, dusty clouds close to the nucleus a huge burst of star formation (Starburst) occurs, heating the dust by starlight. OH Megamasers – very luminous (up to 10^4 $L_\odot$) masers (microwave lasers) emitted by OH radicals – are extraordinarily powerful radio spectral lines found in some of these galaxies. The pumping scheme for OH Megamasers is not certain, but many models[3,4] suggest that absorption of far-infrared photons pumps the masers radiatively. Arp 220 is the prototype OH Megamaser galaxy[5], and we report here the first detection of its 35μm OH absorption. We find that the power absorbed in this line alone can pump the masers, providing the first direct observational support for radiative pump models, and that the IR pumping continuum probably arises in a warm extended region more consistent with a Starburst than with an Active Galactic Nucleus model.

Details of the mechanism generating the maser emission in astrophysical sources (Megamaser galaxies and, in our own galaxy, star formation regions and winds from evolved stars) are still somewhat uncertain. For the Megamaser galaxies a good correlation exists between OH maser luminosity and the square of the FIR luminosity, especially that measured in the IRAS 60μm band[6,7], consistent with an IR radiative pump. In fact, many OH Megamaser galaxies are Ultra-Luminous InfraRed Galaxies (ULIRGs: 8 to 1000μm luminosities greater than 10^{12} $L_\odot$, where $L_\odot$ is the solar luminosity), and all have huge far-infrared luminosities. It has been suggested that ULIRGs may be created by the merger of two galaxies[1], and Arp 220 indeed appears to be the result of such a process[8,9]. VLBI radio images[10,11] of it show that the OH

Megamaser emission arises in regions only a few parsecs in size in the core of the galaxy, and have been used to support Active Galactic Nucleus (AGN) models for Arp 220.

OH has strong transitions at 35μm and 53μm, and it is suspected that the masers may be pumped radiatively via absorption in these lines, exploiting the powerful infrared emission of the host galaxy. Such models[3,4] posit that absorption of photons via the above two transitions excites the OH radicals. There follows a radiative cascade to lower levels via other far-IR transitions, principally those at 79, 96, 98, 119 and 163μm, with transitions from the 35μm pumped level ($^2\Pi_{1/2}$ J=5/2) inverting the ground state Λ-doublet levels responsible for the 1667MHz maser. These models suggest for Arp 220 that the maser emission arises predominantly in very small, dense clouds, near the nucleus.

We observed the 34.97–35.54μm spectrum of Arp 220 with the Infrared Space Observatory's Short Wavelength Spectrometer (SWS). After processing the spectrum has a resolving power of about 1200, and is presented in Figure 1. At 35.45μm the [SiII] line (rest wavelength 34.814μm) is seen in emission. The OH rotational transition is split into two Λ-doublet states with wavelengths of 34.629 and 34.603μm. Hyperfine splitting of the doublet components is small (a few km/sec), and safely ignored in this analysis. The mean multiplet rest wavelength is 34.616μm. The blended OH lines are apparent as a single resolved feature with maximum optical depth 0.21 at 35.23μm, yielding a velocity redshift of 5320 km/sec.

To analyse the OH absorption, we derived the photon flux, and shifted the data into the rest frame, adopting a redshift of 5380km/sec[5,10]. We assumed that the Megamaser emission and the IR absorption are isotropic, and adopted a distance to Arp 220 of 72Mpc[8]. We determined a baseline for the OH absorption by fitting a linear continuum, and then inverted the absorption to obtain the spectrum presented in Figure 2, showing the photon absorption rate in the OH transition. Integrating across the line, the total absorption is 2.3×10^{55} photons/second.

The luminosity of the 1667 MHz OH Megamaser line in Arp 220 is 1.4×10^{36} erg/second[5], assuming isotropic emission, or 1.3×10^{53} photons/second. The 1667 MHz line accounts for about 70% of the total OH Megamaser emission from Arp 220[4], the rest being in lines at 1612, 1665 and 1720MHz. The radiative pump models so far constructed[3,4] can attain pump efficiencies as high as 1%, so the 35μm absorption in Arp 220 is consistent with the models, and in fact could power the observed OH masers on its own. In practise, the 53μm transition should also play a role. This is the first time a far-IR OH transition has been observed in a Megamaser galaxy, and provides the first direct observational support for the radiative pump models. From the strength of the OH absorption, we can estimate an OH column density of 4×10^{17} cm^{-2}, just slightly lower than predicted by some models[3,11]. For a single absorbing cloud of radius 1pc[11], the OH density is about 0.1cm^{-3}, much higher than predicted by models[4]. From the OH column density we determine the OH excitation temperature[1] to be 46K (for an isothermal OH column), very similar to the estimate from radio maser lines[1]. For an $[OH/H_2]$ abundance ratio of 10^{-6}, appropriate for chemical equilibrium in warm gas[3,12], this yields a total gas column density of 4×10^{23} cm^{-2}, which assuming the mean Galactic reddening law[13] yields a reddening $A_v \approx 200$, and a 35μm optical depth close to 1. Other observations have been used to estimate $A_v \approx$ 50–1000 for Arp 220[14,15]. The above calculations are very crude, and subject to numerous simplifications (namely, the absorbtion originates from a single cloud with uniform temperature, and the dust-to-gas ratio and dust absorbtion properties for the absorbing cloud are similar to those for the interstellar medium in our galaxy). However, the consistency of the results with those of other independent studies implies that they are at least of moderate accuracy.

From the continuum flux and the absorption depth we can make some general inferences about the absorbing regions. Models have presumed the pumping IR radiation to come from warm dust embedded in the maser cloud itself[3,4], and derived dust temperatures around 60K for a 3pc cloud. At the line center, 9Jy of continuum is absorbed. Because the maximum (black-body) flux at 34.8μm from a 60K, 3pc cloud at the distance of Arp 220 is only 0.2mJy, compared with the observed 9Jy absorption, this model clearly does not work (a much larger or warmer dusty region is needed to supply the 34.8μm photons for absorption). VLBI results[11] in fact reveal maser regions with sizes of $\leq$ 1pc, with spatially coincident continuum hotspots of comparable size surrounded by a larger ($\approx$100pc) diffuse source. The ISO data allow us to determine the minimum parameters of such regions. If most of the observed 63Jy comes from the diffuse region, at a level of 54Jy, and the remaining 9Jy represents the flux from a hot inner (pump) region which is then 100% absorbed by OH in the diffuse region, the latter region must be at least as hot as 180K (if it emits as efficiently as a blackbody), in order to supply the required 54Jy. If the IR-pumping cloud itself is as small as 1pc, the 9Jy it contributes at 35μm , which is fully absorbed by the OH cloud, implies its temperature is at least 21000K if it emits as a blackbody; if its size were the 3pc suggested above, the corresponding temperature would be 2400K. The high colour temperature and compact nature of the former would imply an obscured AGN, while the latter temperature and size would be more consistent with a starburst. The complete lack of any high ionization spectral lines, which are AGN diagnostics, in the spectra of Arp 220[14,15] render an AGN model unlikely, unless the extinction is very much higher even than we estimate above. We therefore conclude that a more consistent picture emerges from an extended starburst scenario. The maser emission may be beamed (that is, the coherence is directional) in order to make the region appear small in OH, and so the OH cloud may be as large as the entire starburst or very much smaller. An AGN is not required, nor is one indicated by these data, though we cannot rule its presence out.

If the OH radicals absorbing at 35μm are pumping the radio maser lines, then the absorption should, in principle, have the same Doppler broadened profile as the maser lines. The 35μm OH multiplet comprises six hyperfine split lines. The separation of the dominant multiplet members is 0.026μm or 225km/sec[16]. The FWHM of the line core is 490km/sec (0.058μm) and that of the underlying pedestal 940km/sec (0.11μm). The 1667MHz maser line in Arp 220 has a core with a FWHM of 130km/sec and a pedestal with a FWHM of about 250km/sec[5,11]. Convolution of the SWS spectral response with the intrinsic line width as indicated by the maser lines indicate that we should expect a core FWHM of about 430km/sec and a pedestal FWHM of about 680km/sec. Thus the pedestal width is about 30% larger than might be expected from the radio observations, but the core, which contains the majority (about 80%) of the line flux, is as expected. The pedestal is roughly symmetric, which is consistent with the radio maser line profile except for the discrepant width. The maser gains should be greater than 1 in Arp 220[4]. In a given line component (either the pedestal or the core), the maser amplification will be preferentially strengthened at the strongest velocities, 'narrowing' the OH maser line. This might explain the comparison between our ISO absorption pedestal and the maser line pedestal. Alternatively perhaps not all of the absorbing cloud generates masers, or does so along our line-of-sight, and the extra velocity width in absorption corresponds to unseen masers or unamplified components. Losing half the absorbed photons to unseen masers would not affect our conclusions. Alternatively, Keplerian velocities in the IR source may be sufficient to explain the width of the absorption pedestal[11].

Our ongoing ISO program will observe OH transitions at 35, 53, 79, 96, 98, 119 and 163μm in several Megamaser galaxies and OH/IR stars. These observations should provide a more comprehensive test of the accuracy of radiative pump models, by charting the course of the radiative cascade through the OH energy levels, and by determining the power absorbed in all the pumping lines. These results are unlikely to qualitatively change the results presented here, but may refine them numerically by as much as several tens of percent. The primary difficulty remaining regarding the origin of the far-IR luminosity of Arp 220 is the determination of the extinction to the power source. Other studies have shown that if the extinction is as high as we have determined, then the strengths of low excitation spectral lines are consistent with a starburst[15], while the high excitation lines required by an AGN are so far undetected. An unambiguous determination of the extinction can thus confirm the presence of a starburst. If, however, the extinction can be shown to be much lower than we have determined, this would argue against the presence of either a starburst or an AGN, leaving the origin of the far-IR luminosity of Arp 220 highly mysterious.

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Figure Captions

Figure 1: ISO SWS spectrum of Arp 220. The emission feature at about 35.45μm is due to [SiII], and the strong absorption centered around 35.23μm is the OH 35μm multiplet. Both the observed wavelength (bottom scale) and the rest frame wavelength, corrected for a 5320 km/sec redshift (top scale), are indicated.

Figure 2: the strength of the OH absorption, as an absolute flux at the source assuming isotropic emission. The integrated absorption strength from this spectrum is 2.28×10^{55} photons/second.

Figure 1

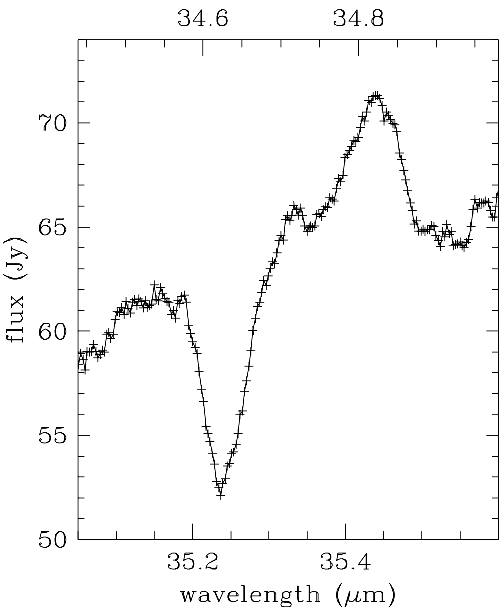
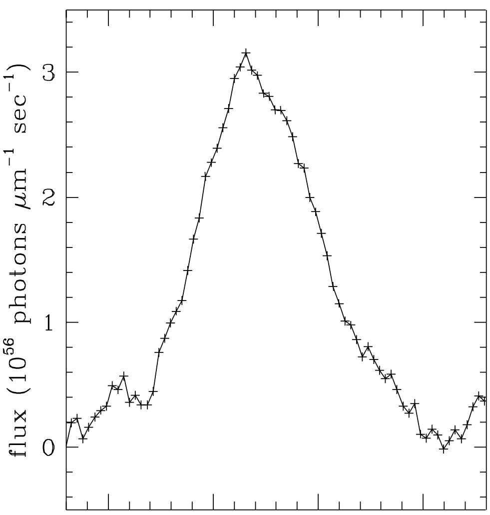


Figure 2



flux (10^56 photons μm^-1 sec^-1)
0
1
2
3
34.55
34.6
34.65
34.7
wavelength (μm)