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MID INFRARED HYDROGEN RECOMBINATION LINE EMISSION FROM THE MASER STAR MWC 349A

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ABSTRACT

We have detected and spectrally resolved the mid-IR hydrogen recombination lines H6α (12.372μm), H7α (19.062μm), H7β(11.309μm) and H8γ(12.385) μm from the star MWC349A. This object has strong hydrogen maser emission (reported in the millimeter and submillimeter hydrogen recombination lines from H36α to H21α) and laser emission (reported in the H15α, H12α and H10α lines). The lasers/masers are thought to arise predominantly in a Keplerian disk around the star. The mid-IR lines do not show evident signs of lasing, and can be well modeled as arising from the strong stellar wind, with a component arising from a quasi-static atmosphere around the disk, similar to what is hypothesized for the near IR (≤4μm) recombination lines. Since populations inversions in the levels producing these mid-IR transitions are expected at densities up to $\sim 10^{11}$ cm^{-3} , these results imply either that the disk does not contain high-density ionized gas over long enough path lengths to produce a gain ~1, and/or that any laser emission from such regions is small compared to the spontaneous background emission from the rest of the source as observed with a large beam. The results reinforce the interpretation of the far-IR lines as true lasers.

Subject Headings: circumstellar matter - stars: emission-line, Be - stars: individual (MWC349A) - stars: mass loss - infrared: sources - infrared: spectra, masers

I. INTRODUCTION

MWC349A, the brightest radio continuum star in the sky, has a strong bipolar wind with mass loss estimated at $\sim 10^{-5}\ M_\odot\,yr^{-1}$ (Cohen *et al.*, 1985), or even as much as $\sim 9\times10^{-5}\ M_\odot\,yr^{-1}$ (Martin-Pintado, Bachiller, Thum and Walmsley, 1989). It is surrounded by a Keplerian disk of ionized gas seen edge-on (e.g., Hamann and Simon, 1986; Gordon, 1992; Thum, Martin-Pintado and Bachiller, 1992; Ponomarev, Smith and Strelnitski, 1994, hereafter Paper I; Strelnitski, Smith and Ponomarev, 1996, hereafter Paper III). The source is so far the only confirmed emitter of strong hydrogen recombination line masers and lasers in the millimeter (e.g., Martin-Pintado *et al.*, 1989a,b) and far infrared (Strelnitski *et al.*, 1996). Laser emission (for simplicity we will use the term laser when both maser and laser are meant) is seen in a series of Hnα lines (that is, transitions with $n+1 \rightarrow n$) starting from about the H40α line at 135GHz (2.22 mm) and extending down at least as far as the H15α line at 169μm (Strelnitski *et al.*, 1996, hereafter Paper IV), with likely amplification seen even at the H10α line at 52.5μm (op cit.), and in one Hnβline, the H32β at 366 GHz (Thum *et al.*, 1995).

Continuing from both ends of this string of lasing lines are many other recombination lines which have been reported from this source. At radio wavelengths lines have been reported out to the H92α line at 3 cm (Rodriguez and Bastian, 1994), and from the opposite extreme they continue through the near infrared H4α (4.05μm, Hamann and Simon 1986) into the visible H2$\alpha \equiv$Hα (6524Å, Kelly, Rieke and Campbell, 1994). In addition in the near IR higher order recombination lines are seen -- Hnβ, Hnγ, and above (e.g., Kelly, Rieke and Campbell; Hamann and Simon, 1988). Absent from this long series of transitions, covering over four orders of magnitude in wavelength, are the lines in the critical region between 4μm and 52.5μm. The mid-IR range is important for two reasons. First, somewhere in this region the detected lasing disappears, despite theoretical indications that the populations of the corresponding levels are inverted. Observationally the strength of the lasing is seen to steadily decrease to the short wavelength side of the peak in the submillimeter where the excess above the expected spontaneous emission is a factor of ~200 (Paper III and Paper IV) to small values (~x6) at 52μm, just as on the long wavelength side the maser action appears to die off longward of about the H40α line (e.g., Paper III). The second reason for its importance is that the mid-IR lines, if lasing, would sample higher density gas thought to arise at the inner edges of the disk, closer in than the ~5AU modeled for the H15α line (Paper IV). In this paper we report on velocity resolved infrared spectra of four recombination lines in this interval, and discuss their relative intensities and profiles.

A great advantage of the masing transitions has been that the strong, velocity resolved emission of this sequence (albeit complicated by the fact they show substantial time variations) enables the detailed modeling of the environment. The bipolar wind is recognized as being the source of the strong radio continuum flux, and of the non-masing centimeter radio recombination lines (Rodriguez and Bastian, 1995). Although early suggestions also proposed it as the source of the intense maser lines (Martin-Pintado *et al.*, 1989a,b) it is now clear that at least the strong, double-peaked emission arises from the disk and not the wind (e.g., Gordon, 1992; Thum, Martin-Pintado and Bachiller, 1992). A portion of the "pedestal component" may also arise in the wind. A specific model has been proposed for such "photoevaporated" Keplerian disk structures by Hollenbach *et al.* (1994), and has been used to obtain physical parameters of the disk (Paper IV). The non-masing near-IR and optical hydrogen recombination lines, as well as a plethora of other atomic lines, have been attributed to various zones of ionization along the radius of the Keplerian disk (Hamann and Simon, 1986), as have the lasing far-IR lines (Paper IV).

Maser and laser amplification in the submillimeter and FIR lines implies quite high densities, $N_e > 10^{6\text{-}7}$ cm^{-3} (e.g., Paper I; Strelnitski, Ponomarev and Smith, 1966, hereafter Paper II). The presence of very high densities of circumstellar ionized gas in this source, even as high as $N_e \geq 10^{10}$ cm^{-3}, was proposed by Hamann and Simon (1986; 1988) to explain the emission from [FeII], [FeIII]. Kelly, Rieke and Campbell (1994) also found evidence for densities $N_e \geq 10^6$ cm^{-3} in their near-IR spectra. Earlier, Smith, Larson and Fink (1979) suggested lasing in the abnormally bright infrared hydrogen Pfβ line from Orion/BN, but noted that at the high densities implied ($>10^{10}$ cm^{-3}) improved models for the hydrogen levels populations were needed to model the line strengths. Hummer and Storey (1992) and Storey and Hummer (1995) have recently provided such calculations, with densities that extend beyond $N_e \geq 10^{10}$ cm^{-3}. We have used their tables (Papers I, III and III) to model the maser and laser emission from MWC349, and in particular to confirm the prediction that population inversions persist to these high densities. As the transitions having maximal laser gain shift steadily towards lower quantum number n as the density increases, at densities above Ne > 10^{7-8} cm^{-3} the far and mid infrared Hnα lines are expected to be efficient amplifiers. Moreover the very large gain coefficients expected from even modest sized regions with such high volume densities. Since the gain is nominally proportional to the density squared, the H7α line for example has its characteristic length as only 3×10^9 cm at $N_e \geq 10^{10}$ cm^{-3} (c.f. Paper II), suggesting these lines might be detectable and useful probes of the inner few AU.

We observed a set of mid-IR recombination lines to determine whether, given the theoretical possibility of inverted populations and high gains, the trend of observable lasing lines continues down into the mid IR in MWC349A, and to determine whether this enables us to refine further the parameters of the Keplerian disk. The result might help shed further light on the remarkable fact that despite the ubiquitous inversions predicted in hydrogen only MWC349A to date shows unambiguous and strong laser emission. In this paper we report our results: velocity resolved observations of four mid-IR hydrogen recombination lines from MWC 349A -- the H7α line at 19.062μm, the H6αline at 12.372μm, the H7βline at 11.309μm, and the H8γ line at 12.385μm.

II. OBSERVATIONS AND ANALYSIS

a) Instrumental and Observational Summary

The hydrogen recombination lines were measured from the NASA Infrared Telescope Facility on the nights of June 7 and 8, 1994, with a followup search for time variability one year later, in July 10, 1995. Table 1 shows a log of the observations. The Irshell spectrometer used either a 1" or 2" slit width (depending on seeing conditions) and had a resolution of 20-30 kms^{-1}. Flatfielding was done using a dome-temperature card chopped against the sky. Atmospheric corrections were done by observing the standard χ Cyg immediately before and after each observation, flatfielding in the same way as the source spectrum, normalizing the average spectrum to unity, and dividing it into the source spectrum. Flux calibration was done by normalizing the continuum flux of the observed spectra to an average spectrum generated by fitting the photometric observations between 9 and 20 μm of Simon (1974), Simon and Dyck (1977), Herzog, Gehrz and Hackwell (1980), and Aitken *et al.*, (1990). Velocity calibration was done using the telluric lines in each spectrum. In general the fluxes are precise to 5-10%. Data files were processed using Irshell's own software; further information on the instrument can be found in Lacy *et al.* (1989).

Figure 1a shows the 19μm spectrum, as well as four gaussian profiles into which it can be decomposed. Figure 1b shows the 12.4μm spectrum containing both the H6α and H8γ lines, along with its gaussian decomposition. Figure 1c shows the 11.3μm spectrum containing the H7β line. The locations of weak telluric features are also marked throughout. Table 1 lists the observed parameters of the four measured lines and their decompositions; repeat observations in 1995 showed no variations from these.

b) Lasing, or Optically Thin Emission ?

In presenting their analysis of the FIR lasing lines H15α, H12α and H10α, Strelnitski *et al.* (Paper IV) point out the trend, first described by them in Paper III, that the integrated Hnα lines fluxes in the millimeter and far IR regime (H36α - H10α) deviate in intensity from that expected from optically thin, spontaneous emission. The latter is shown to be a smooth curve nominally proportional to n^{-6} to n^{-8}, where n is the principal quantum number, and the range in exponent is due to the increasing importance of free-free absorption at the longer wavelengths. Strelnitski *et al.* (1996) use this excess emission over the optically thin value to show that the FIR lines measured from the KAO are lasing, but with a smaller amplification than the maximal amplification values seen in the submillimeter. The integrated values of the two mid-IR α-lines presented here fall close to the expected spontaneous emission values predicted by the aforementioned dependence, providing evidence that the net emission in these lines has indeed not been significantly amplified. In the next section we show this in more detail.

c) Emission from the Wind and the Disk

The source structure of MWC349A is complex. Hamann and Simon (1988) delineate at least five different emission regions, and Kelly, Rieke and Campbell (1994) also find evidence for each of them in the near-IR. Rodriguez and Bastian (1994) observed the H92α line and conclude the bipolar wind is itself rotating. Finally the variability and asymmetries of the maser line profiles (e.g., Thum *et al.*, 1994) indicate both complex substructure in the disk and possible infall. Many of these structural subtleties are still under debate, but we think it is safe to admit that at least two distinct regions contribute to the recombination line fluxes we present here: the bipolar wind, and the quasi-static, ionized atmosphere of the Keplerian disk.

In order to estimate the contribution to the mid-IR fluxes from the bipolar wind we normalize the calculation to the flux in the H92α line measured by Rodriguez and Bastian (1994), and Rodriguez (private communication) at $(7.6 \pm .8) \times 10^{-27}$ W/cm^2. Unlike the H66α line, for which there is at least one suggestion it has some component of masing in the wind (Martin-Pintado *et al.*, 1993), the H92α line shows no evidence for anything except normal emission from a strong, ionized wind. Indeed the radio *continuum* emission from MWC349A follows an $L_\nu \propto \nu^{0.6}$ law down to wavelength of about 100μm, as is characteristic of such an optically thick flow. The hydrogen lines from such a wind sample surfaces of optical depth $\tau \approx 1$. Their (normalized) fluxes are calculated assuming the wind has a constant velocity flow $V=V_i(r/r_i)^s$ with s=0 (e.g., Smith, Fischer, Geballe and Schwartz, 1987; Panagia and Felli, 1975). The results are plotted as the solid line in Figure 2; fluxes for the entire series of Hα lines from H4α to H16α (wavelengths indicated by triangles on the x-axis), including those lines not yet reported, have also been calculated and plotted. The measured fluxes are remarkably close to those extrapolated from the H92α flux, but they are stronger by a factor of 1.8 for H6α and 2.0 for the H7α lines. The same model finds the H7β and H8γ line fluxes are consistent with a wind to within their measurement errors, and these results are shown in Figure 2 as small open triangles that virtually overlap the measured data points (the curve refers only to the α-line transitions). The Brα line flux is also about 90% higher than the wind prediction. The lasing H15α line is, of course, 35 times brighter than this model. The 10% uncertainty in the H92α flux we have taken as a reference is not enough to explain these deviations from the wind prediction.

There are several possible sources for these deviations from wind model predictions. First, even a small change in the wind parameters, for example a modest acceleration like s=0.5 instead of s=0, would be more than enough to boost the near and mid-IR line fluxes when extrapolated from the H92α line which is produced so far away (see the discussion and relations in Smith, Fischer, Geballe and Schwartz, 1987). However, Hamann and Simon (1988) note that their [FeII] emission might suggest deceleration; this would push the predicted fluxes of the H lines even further from those observed. Alternatively, as noted above, the wind itself may have very complex structures and/or motions. We have generally adopted (see also Strelnitski *et al.*, 1996) the generic "weak wind" model of Hollenbach *et al.*, (1994) for this source to describe aspects of the disk flaring and wind, but note that they too call attention to the fact that for MWC349A their model has difficulty describing the observed emission within the inner 30 AU.

We note that their model predicts an $n \propto r^{-3/2}$ dependence to the flow, whereas the continuum data seem to be consistent with a $1/r^2$ wind (e.g., Cohen *et al.*) which we have adopted to fit the line fluxes.

We think that the most probable cause of the deviations from wind models is that the morphology of the emitting ionized gas around MWC 349A is not limited to the wind. In particular, in the Hollenbach *et al.* model the stellar ionizing photons maintain an HII-region like atmosphere above the disk, including the region of the inner zone where the near and mid-IR lines are expected to arise. Hamann and Simon (1986) attribute the location of the Brα line to such a consistent location: the double-peaked profiles and/or asymmetries of the shorter wavelength lines are strong indications of their originating in a rotating disk rather than in a bipolar wind. We therefore modeled the residual (i.e., non-wind produced) fluxes as arising from a static, optically thin HII region, and calculated the values from the Hummer and Storey Case B emissivities for the case of $T=10^4$K and $N_e=1\text{x}10^7$ cm^{-3} ; the conclusions are not particularly sensitive to the exact values of either T or N_e. Figure 2 plots the sum of the contributions to the lines, wind plus "HII region", where we have normalized the latter contributions by the total flux in the Brα line minus the predicted wind contribution.

Using the canonical value for extinction in this source, A_V=10 mag (Cohen *et al.*), the total Brα flux is $3.0\text{x}10^{-17}$ W/cm^2 (Hamann and Simon, 1986), with about half the flux contributed from the strong wind. The predicted "HII region" contributions to the mid-IR lines, when normalized to the remaining Brα flux, are rather close to those observed: only about 20% above the observed values for both the H6α and H7α lines. If the assumed extinction is too high, the intrinsic flux of Brα is reduced and all the predictions fall even closer to the measure values. The current extinction value is derived by Cohen *et al.*'s analysis of the photospheres of both MWC349A and MWC349B. They find the extinction to MWC349A is about 2 mag larger than that for MWC 349B, and they speculate that this extra extinction is likely due to the effects of the edge-on disk, while that of the other 8 mag of extinction is probably foreground dust. If the Brα and mid-IR lines arise in a region outside of the disk, they might not experience all of this additional extinction. Given the other general uncertainties in the physical structure of this inner region, and the wavelength dependence of the extinction itself, we conclude that an extinction between A_V=6-10 mag can adequately describe all the mid-IR line fluxes. We note that Kelly *et al.*(1994) also estimate an $A_V \approx 11$ mag from the near-IR hydrogen and helium line ratios. Because at wavelengths shorter than 4.05μm the size of the extinction correction becomes very large and sensitive, we have not attempted to fit or model the many shorter wavelength line fluxes that have been seen.

The plots in Figure 2 also illustrate that no combination of wind and static atmosphere such as we have considered here is able to explain the very strong measured FIR fluxes in the H15α, H12α, and H10α lines reported by Strelnitski *et al.*. Our results confirm that these lines do indeed show sign of significant amplification: hence, lasing.

III. THE VELOCITY COMPONENTS

The four observed mid-IR lines show velocity structure spanning as much as 170 kms^{-1} (figures 1a-d). When the lines are fit to a single gaussian profile their peak velocities and their widths closely match (see Table 3): $V_{LSR} \approx +12 \pm 2$ kms^{-1}, $\Delta V(FWHM) \approx 90 \pm 8$ kms^{-1}. This value for V_{LSR} is comfortably close to that of the star: +8kms^{-1} (Thum *et al.*, 1995). The high SNR of the data make it tempting to try to attribute some of the velocity structure we observe, especially in the H7α line, to the several wind or disk components of the emission. A two component fit to the profile of H7α gives +30 kms^{-1} (strong component) and -17 kms^{-1} (weak component), quite close to the values seen in the double-peaked Brγ line (Hamann and Simon, 1986), and to the weakly defined ~+37kms^{-1} feature they find in the Brα line, which they attribute to the surface of an inner wind evaporated from the disk. Hamann and Simon show that a bipolar flow viewed approximately edge-on, as in the case of MWC 349A, is not by itself able to explain the line structure they observe, and conclude some disk-like rotation is needed; indeed this is the origin of the submillimeter lines' structures. If we compare the fluxes in the bright (that is, the positive velocity) components of our two mid-IR α-lines with those predicted from our previous wind model calculations, we find agreement to within 30%. The high velocity component of the H6α is weak, however, and cannot by itself account for the flux from an ionized, static atmosphere component (normalized as above to an intrinsic total Brα line flux of 3.0×10^{-17} W/cm^2). The negative velocity components are themselves weakly subdivided (Table 1): each of the two α-lines contains a doublet at high negative velocities separated by about 65±5 kms^{-1} . (We note that possible contamination from the He I 7-6 line at this velocity should be 10 time weaker.) In a Keplerian disk, such as that considered by Strelnitski, Smith and Ponomarev (1966), the velocity at 30AU from the star is ~50 kms^{-1} (as measured by the H30α maser line velocity and the interferometric observations of Planesas *et al.*, 1992). Hence if some of the velocity pair structure we see in the IR line emission arises from the disk, this velocity separation suggests a region located at about 25-30 AU from the star. Strelnitski, Smith and Ponomarev show that were laser emission to be present in the H7α line, it would be expected from a much denser region: at a distance of more like 3×10^{12} cm, within the static atmosphere of the Hollenbach model but much closer to the stellar photosphere, where the velocity separatin of the red and blue features would be much greater than that observed. Alternatively the dense regions might exit in knots of material located further out in the disk. Additional observations and temporal monitoring would be helpful in sorting out this possibility.

IV . CONCLUSIONS

We present new observations of four mid-IR hydrogen recombination lines, whose strengths are consistent with conventional emission from the ionized atmosphere around the Keplerian disk of the star, the strong bipolar wind, or contributions from both. There is even mild agreement in the observed velocity structure of the lines. No amplification (lasing) is required in these new lines reported here, and the results confirm and strengthen our earlier conclusions that the FIR lines are lasing. The detailed conditions needed in the source to produce detectable laser emission in the mid-IR lines are discussed in Strelnitski, Ponomarev and Smith (1966). Although the theory of Hummer and Storey (1995) indicates inversions can be present between the levels of all the transitions we report here, considerations of laser saturation and/or possible beaming may make it hard to produce or detect significant amplification (Strelnitski, Ponomarev and Smith). Alternatively it might just be that the densities needed for inversions at, say the H7α line -- between about 2×10^{10} and 2×10^{11} cm^{-3} (*op cit.*) -- don't exist as a distinct disk annular region, perhaps because at these high values the material is too close to the star to retain its Keplerian character (see the "weak wind" model of Hollenbach *et al.*, 1994). These results fill in a portion of the critical infrared wavelength interval within which this remarkable source switches from conventional emission to shining in laser lines from its disk.

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Figure Captions:

Figure 1 a-c: Irshell spectra of the four hydrogen recombination lines detected. Solid and dotted lines show the result of gaussian fitting. The locations of weak telluric features are also indicated.

Figure 2: Observed mid- and far-IR lines, also including the Brα line. The solid line shows the predicted flux in the Hnα lines from a bipolar wind of constant velocity, normalized to the observed flux in the H92α transition at 3.1 cm. The dotted line shows the predicted flux in the Hα lines from both the wind plus a component from a thin HII-region, with the latter contribution scaled to the flux in Brα. The three FIR lines are from Strelnitski *et al.*, 1966. The x-axis is marked with diamonds showing the wavelength locations of all the Hnα lines (H16α - H4α); the theoretical curves were produced by calculating fluxes for each of these lines, and connecting points with straight line segments.

Table 1. Log of Observations

Transition	λ(μm)	UT Date (1994)	$T^{a}_{integration}$ (sec)	Resolution (kms^{-1})
H7α	19.062	June 7	1258	15
H6α	12.372	June 7	419	25
H6α	12.372	June 8	1258	25
H7β	11.309	June 8	210	15

[a] Total on source integration time

Table 2. Integrated Line Fluxes

Transition	λ(μm)	Integrated Line Fluxes[a] ($x10^{-15}$ Wm^{-2})
H7α	19.062	8.7
H6α	12.372	22.0
H7β	11.309	6.5
H8γ	12.387	3.9

[a]Systematic uncertainties are estimated to be ~15%; relative uncertainties are <5%.

Table 3. Line Component Parameters

Transition	V_{LSR} (kms^{-1})	ΔV_{FWHM} (kms^{-1})	Flux ($x10^{-15}$ Wm^{-2})
H7α	30 ± 2	57 ± 3	4.8 ± .3
	-17 ± 2	48 ± 4	2.5 ± .3
	-74 ± 4	33 ± 11	0.2 ± .1
	-144 ± 5	95 ± 13	0.9 ± .1
(single gaussian fit:	13.5	82.4 ± 3	8.7)
H6α	13 ± 1	90 ± 1	17.4 ± 0.3
	-103 ± 7	35 ± 32	0.3 ± 0.3
	-160 ± 17	116 ± 31	1.9 ± 0.6
H7β	14.3± 3	82.6± 4	6.5 ± 0.6
H8γ	11 ± 2	98 ± 6	3.9 ± 0.3