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LETTER

Letter to the Editor

Infrared lasers in the circumstellar disk of MWC 349*

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Abstract. Observations of hydrogen recombination lines were made with the Infrared Space Observatory (ISO) towards the star MWC 349, where the α–transitions at short millimeter and submillimeter wavelengths have been found to be masers. All α–lines in the ISO wavelength range from 2.4 to 190μm (quantum numbers $n = 4$ to 15) were detected. We find that amplification persists down to 19μm ($n = 7$), showing that these lines are infrared lasers. Our measurements permit for the first time a global view of the quantum number range of the recombination line laser/maser phenomenon, and suggest a peak amplification near $n = 19$ in the unexplored region around 300μm. The entire laser/maser phenomenon can be described quantitatively by case B recombination in a plasma with electron densities peaking at 10^8 cm^{-3}, as expected in the corona of the circumstellar disk. In this model, the maser turns off at long wavelengths because the disk dimensions do not permit coherent gain paths longer than ~ 250 a.u. At short wavelengths, inversion ceases probably because the level populations are thermalized as a consequence of trapping of line photons for $n \leq 6$.

Key words: maser – infrared: stars – stars: individual: MWC 349

Table 1. Fluxes F_L of the H$n\alpha$ recombination lines observed with ISO. Transitions from $n = 4$ to 9 falling into the SWS range have a typical spectral resolution $\lambda/\Delta\lambda \sim 1000$. With the LWS the resolution is $\Delta\lambda = 0.29\mu$m for transitions $n = 10$ to 12, and $\Delta\lambda = 0.60\mu$m for $n = 13$ to 15.

n	wavelength, μm	F_L, W m^{-2}	remark
4	4.05	$2.7\,10^{-13}$	Brackett α
5	7.46	$4.8\,10^{-14}$	Pfund α
6	12.37	$1.6\,10^{-14}$	Humphreys α
7	19.06	$9.0\,10^{-15}$	
8	27.80	$6.4\,10^{-15}$	
9	38.87	$5.2\,10^{-15}$	a
10	52.54	$3.3\,10^{-15}$	
11	69.07	$3.1\,10^{-15}$	
12	88.76	$2.1\,10^{-15}$	b
13	111.86	$1.4\,10^{-15}$	c
14	138.65	$9.2\,10^{-16}$	
15	169.41	$8.6\,10^{-16}$	

a: corrected for blend with H11β
b: blended with [OIII]
c: corrected for blend with H16β

1. Introduction

The hydrogen recombination line maser in the peculiar emission line star MWC 349 is one of the rare astronomical masers originating in atomic transitions. Groundbased observations at millimeter and submillimeter wavelengths have shown that the α–lines (transitions $n+1 \rightarrow n$) are strongly amplified for quantum numbers $n \lesssim 36$ (wavelengths $\lesssim 2$ mm), and that their flux increases toward shorter wavelengths down to 453 μm ($n = 21$), the shortest wavelength submillimeter transition observed (Martín–Pintado et al. 1989a, 1989b; Thum et al. 1994a, 1994b). The α–line maser is therefore a very broad band phenomenon, and here we explore its range to still shorter wavelengths using the Infrared Space Observatory (ISO; Kessler et al. 1996).

The maser originates in the dense ionized corona of the circumstellar disk. Due to its brightness and the strong dependence of the amplification on electron density and other factors this maser is potentially an ideal tool for investigating the poorly known kinematics and physical conditions of disks around massive stars.

2. Observations

Using the full wavelength range available with the two grating spectrometers on board ISO we have obtained a continuous

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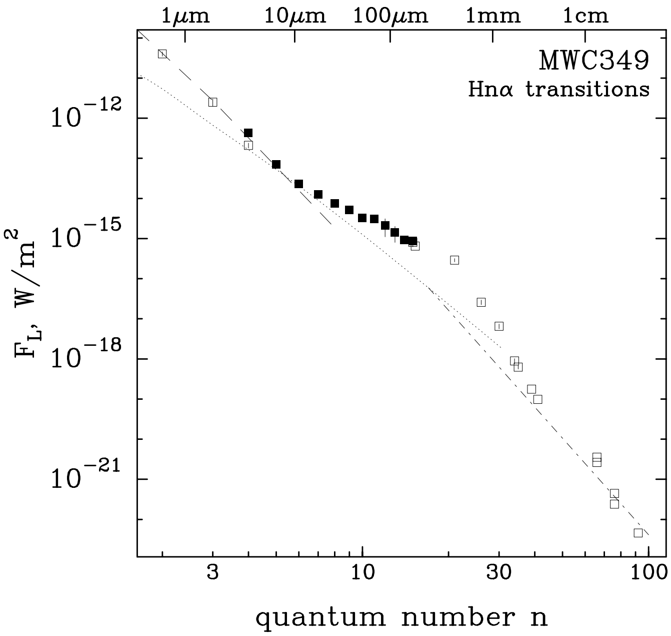

Fig. 1. Flux of hydrogen recombination α–transitions, $\mathrm{F_L}$, in MWC 349. Filled symbols refer to ISO observations (Table 1). Open symbols refer to groundbased (Altenhoff et al. 1981; Thompson et al. 1977; Hamann & Simon 1986; Greenstein 1973; Escalante et al. 1989; McGregor & Perrson 1984; Martín–Pintado et al. 1989a, 1994a, 1994b; Thum et al. 1992, 1994a, 1994b). From the three transitions observed by the KAO (Strelnitski et al. 1996a) we only included H15α (slightly displaced for clarity), the others not being reliable detections. Fluxes are corrected for extinction ($\mathrm{A_V} = 10$ mag; Cohen et al. 1985), using a recent IR reddening law (Lutz et al. 1996). The dotted line is a (case B) recombination model where an electron temperature of 7500 K and an electron density of 10^8 cm^{-3} were adopted. At wavelengths longer than $\sim 300\mu$m, a correction for continuum free–free opacity (see Strelnitski et al. 1996c) was applied (dash–dotted line). The dashed line (slope $\sim \nu^{-2.7}$ fits the $n < 6$ observations (see Sect. 3.1).

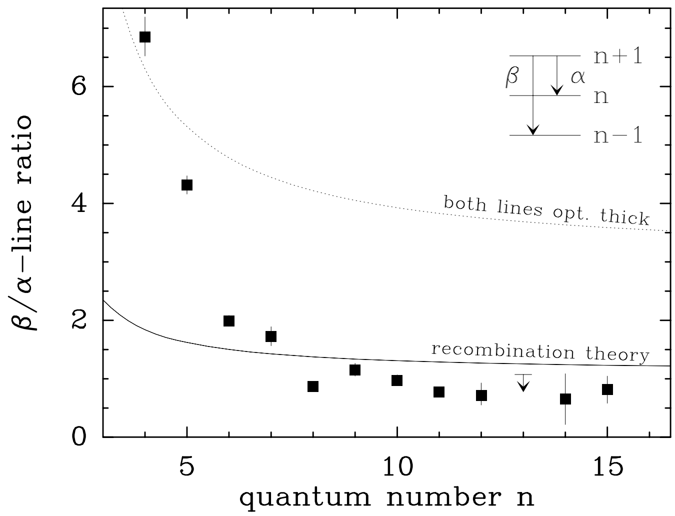

Fig. 2. Recombination line β/α ratios for transitions from a common upper level as depicted in the inset. Data are from this investigation except for Pa$\,\beta$ (Kelly et al. 1994), and were corrected for differential extinction as in Fig. 1. The continuous line is the theoretical case B recombination (spontaneous) ratio. These common upper level ratios do not depend on the detailed physical conditions of the gas, in particular the electron density. The dotted line describes the situation where both lines are optically thick and thermalized. Their flux is then proportional to $\nu^3 R^2(\nu)$, where $R(\nu)$ is the characteristic radius of the source at frequency ν, here assumed to vary as $\sim \nu^{-0.7}$ as for an isotropic wind.

spectrum from 2.4 to 190 μm of the star MWC 349 (Thum et al. 1998). More than 160 emission lines were detected, most of which are recombination lines of hydrogen. In particular, all hydrogen α–lines H$n\alpha$ are detected, from $n = 4$ to 9 at very high signal–to–noise with the Short Wavelength Spectrometer (SWS; de Graauw et al. 1996) and from $n = 10$ to 15 with the Long Wavelength Spectrometer (LWS; Clegg et al. 1996). The fluxes of these lines, which are unresolved with both spectrometers, are listed in Table 1. Errors are dominated by uncertainties of the calibration, which we estimate as 25% (SWS) and 35% (LWS) from residual flux differences between overlapping detectors and from comparison with a few ground–based measurements. A few of the α–line fluxes were corrected for weak blends with higher order transitions or, in one case (H12α), for a strong blend with an [OIII] transition.

3. Discussion

Fig. 1 assembles these line fluxes together with previous α–line measurements of the source. The mm and submm transitions from $n = 35$ to 21 which were previously demonstrated to be masing show up clearly as the high–n part of a bell–shaped hump of increased line flux which stands out above the regularly decreasing (with n) thermal emission. Our ISO data complete the low–n part of this hump which now appears fairly symmetric and smooth. Its quantum number range, peak location and amplitude can now be derived for the first time with some precision.

3.1. Lasers

Arguments that the millimeter transitions in the hump ($n = 30...35$) are masers are based on the following evidence: *(i)* the high flux densities in the maser spikes and their high line/continuum ratio (Martín–Pintado et al. 1989a), *(ii)* their strong time variability (Martín–Pintado et al. 1989b; Thum et al. 1992), *(iii)* their low β/α line ratios (Gordon 1994; Thum et al. 1995), and *(iv)* theoretical expectation of strong negative line absorption coefficients in a dense ionized wind (Walmsley 1990). In the submm regime, where the line profiles remain similar, but the line fluxes are much higher still than those at mm wavelengths, the α–lines must also be masing. At ISO wavelengths where the lines are not resolved we use the velocity–integrated line flux $\mathrm{F_L}$. It exhibits an *excess above* the smoothly decreasing thermal emission, continuing the trend from the submm/mm masers into the infrared.

The dotted line in Fig. 1 describes the prediction of recombination theory (Storey and Hummer 1995) normalized near the non–masing H6α and, at wavelengths longer than $\sim 300\mu$m, corrected for free–free continuum opacity (dash–dotted). It fits the observations outside the laser/maser hump well with the exception of $n < 6$. These line fluxes vary as $\nu^{-2.7}$ (dashed line), considerably steeper than the prediction by recombination theory based on optically thin, spontaneous emission. This is evidence that the α–lines are at least partially optically thick for $n < 6$, a conclusion reached already previously for H α (Thompson et al. 1977) and Br α (Hamann and Simon 1986). Our observation that all transitions between $n = 7$ and 15 are stronger than extrapolated from these optically thick α–lines, supports the argument that the IR lines in the hump are amplified.

A further, more direct argument is based on the flux ratio of β– and α–lines. The continuous line in Fig. 2 is the prediction of this ratio by recombination line theory for the situation where both transitions originate from the same upper level. The measured ratios show that physical conditions in the gas depart from pure recombination at all n. The sense of the departure for $n \leq 6$ is compatible with the α–lines being optically thick. Above $n = 7$ the measured ratios fall consistently below the continuous line which describes optically thin emission. This behavior follows if the lines are amplified. Since the absolute value of the absorption coefficient is always higher for the α–lines (Strelnitski et al. 1996b), they are amplified more and $\beta/\alpha < 1$.

We conclude that *all* α–lines in the line–excess hump are amplified, including those from $n = 7$ to 15 at ISO wavelengths. These transitions are thus *infrared lasers*, and MWC 349 is the first known source (Strelnitski et al. 1996a) of astronomical lasers.

3.2. A simple model

Normalization of the line fluxes by this first order thermal model shows the laser/maser hump in greater detail (Fig. 3), in particular its quantum number range (from $n_{\tt on} = 7$ to $n_{\tt off} \sim 36$) and its peak at $n_{\tt max} = 19 \pm 2$ where the amplification is $\gtrsim 40$. These observed properties can be understood from tables of the hydrogen recombination line absorption coefficient $\kappa^{\rm L}$ as a function of n and electron density $\rm n_e$ (Walmsley 1990; Storey and Hummer 1995). For increasing $\rm n_e$ the quantum number range where $\kappa^{\rm L}$ is negative, and hence masing is possible, gradually shifts towards smaller n. The resulting behavior of $\kappa^{\rm L}$ is concisely summarized in Fig. 8 of Strelnitski et al. (1996b), which shows that amplification peaks at the measured $n_{\tt max}$ for $\rm n_e = 10^8$ cm^{-3}. We take this to constitute the maximum $\rm n_e$ in the source, in accordance with an investigation of its Paschen decrement (Thum and Greve 1997). Lower density components must also be present, however, since the level inversion rapidly decreases for $n > n_{\tt max}$ in a 10^8 cm^{-3} plasma and ceases altogether near $n = 30$, at variance with the observation. These lower $\rm n_e$ components may also generate masers in their specific quantum number ranges which are shifted to $n > n_{\tt max}$.

For a more quantitative understanding of the resulting amplification pattern we investigated the simple model of a linear maser of total length L, which consists of an unsaturated core and surrounding saturated zones. Following the formalism developped by Elitzur (1992) maser growth is exponential in the core, but linear in the saturated zones. From the range of available $\rm n_e$, the model maser selects for each n the optimum $\rm n_e$ where $|\kappa_L|$ is largest (Strelnitski et al. 1996b). Varying the only two free parameters, L and the optical depth of maser saturation τ_S, we obtain a reasonable fit to the observed amplification pattern (Fig. 3) for $L \simeq 60$ a.u. and $\tau_S \simeq -1$ as long as $n \lesssim 26$. The higher n masers require progressively longer paths, up to $\sim 3L$ at $n_{\tt off}$. We therefore propose a simple picture where the $n \lesssim 26$ lasers/masers all propagate along similar paths roughly parallel to the disk surface, probably somewhat interior to the H30α maser at ~ 40 a.u. from the center (Planesas et al. 1992). The $n > 26$ masers are probably located further out on the disk where $\rm n_e$ is lower and longer paths are geometrically possible. The outer disk radius, ~ 200 a.u. (White and Becker 1985), is of the order of $3\,L$ suggesting that the size of the disk limits the quantum number range of the maser at large n by limiting the maser gain.

At the other end of the quantum number range the transition between optically thick thermal line emission and amplification is very sharp at $n_{\tt on}$, only slightly higher than the case B prediction ($n = 5$) for a 10^8 cm^{-3} plasma. While H5α photons are still trapped in the disk plasma and help to thermalize the level populations, H7α photons may escape, possibly in the vertical direction, thus driving the level populations towards case B, i.e. inversion.

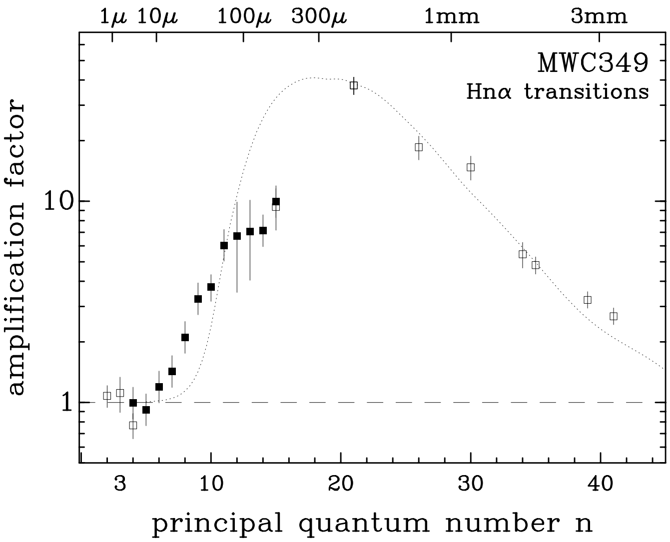

Fig. 3. Factor by which the velocity–integrated line flux of an α–transition is amplified by laser/maser action. Data are as in Fig. 1, but normalized to the thermal model as described by the lines in Fig. 1. The dotted curve is a linear laser/maser model as described in Sect. 3.2.

4. Conclusion

The density structure of disk coronas which are photo–ionized by massive central stars has been investigated theoretically (Hollenbach et al. 1994). These models give the electron density at the base of the corona as a function of radial distance for several stellar masses. The model with a zero age main sequence star

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of 26 solar masses, such as derived for MWC 349 from the mm masers (Thum et al. 1994a), predict $n_e \sim 10^8$ cm^{-3} at 40 a.u. where the H30α masers are located. This remarkable agreement between theory and observation underlines that the laser/maser phenomenon observed here for the first time in its full extent occurs naturally in a configuration of a massive star surrounded by a dense disk. It is only required that the disk is seen roughly edge–on and that it is sufficiently large for the coherent gain paths along its surface.

These natural, single–pass, and high–gain lasers are powerful astrophysical tools for the investigation of the hot environment of massive young stars. The short–lived and small–scale, but energetic phenomena during the evolution of gaseous disks may be particularly promising targets. More objects like MWC 349 may be detectable when more sensitive spectrometers and more observing time becomes available near wavelengths of 300 μm where the recombination line laser/maser peaks.

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