Far-Infrared Hydrogen Lasers in the Peculiar Star
MWC 349A

Vladimir Strelnitski,* Michael R. Haas, Howard A. Smith,
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Far-infrared hydrogen recombination lines H15α (169.4 micrometers), H12α (88.8 micrometers), and H10α (52.5 micrometers) were detected in the peculiar luminous star MWC 349A from the Kuiper Airborne Observatory. Here it is shown that at least H15α is strongly amplified, with the probable amplification factor being greater than or about equal to 10^3 and a brightness temperature that is greater than or about equal to 10^7 kelvin. The other two lines also show signs of amplification, although to a lesser degree. Beyond H10α the amplification apparently vanishes. The newly detected amplified lines fall into the laser wavelength domain. These lasers, as well as the previously detected hydrogen masers, may originate in the photoionized circumstellar disk of MWC 349A and constrain the disk’s physics and structure.

Soon after the invention of the maser and laser (microwave and light amplification by the stimulated emission of radiation, respectively), natural masers with amplifications A up to 10^4 were discovered in interstellar and circumstellar gas clouds (1), first at centimeter wavelengths and later in the millimeter and submillimeter domains, down to wavelengths λ ≈ 0.45 mm (450 μm) (2, 3). The search for natural masers (or, rather, lasers) at still shorter wavelengths is severely hampered by the opacity of our atmosphere. In fact, through most of the 100- to 20-μm region, ground-based observations are impossible.

Masers and lasers work on the same physical principle. In the laboratory, the distinction made between them is based on the technology used to create them, with the wavelength boundary lying roughly at several hundred micrometers (4). A natural dividing principle in astrophysics is the detection technology; the microwave (“wave detecting”) technique used for masers and the optical (“quantum detecting”) technique used for lasers. This boundary roughly coincides with that between laboratory masers and lasers and also with the above-mentioned 300-μm observational barrier.

There is no reason to doubt the existence of astrophysical lasers. For example, calculations have predicted population inversions (5)—a necessary condition for amplification—and, in some cases, the possibility of high gains (6) in the optical and near-infrared hydrogen transitions in HII regions (which are hydrogen clouds ionized by the ultraviolet radiation of nearby hot stars). Yet there is a puzzling lack of observed astrophysical lasers. In 1979, Smith et al. (7) reported an abnormally bright line at λ = 4.7 μm in the spectrum of the Becklin-Neugebauer object in Orion. The line was identified as the hydrogen Pβ transition and, on the basis of an analysis of level populations, it was argued that it might be lasing. However, when this observation was repeated, the line was not as bright (8). Within the solar system, there is strong evidence for population inversions in the 10-μm CO bands in the martian and venusian atmospheres (9). However, the predicted amplifications are very small (A ≲ 1.1) and are not yet sufficient to discriminate observationally between lasing and spontaneous fluorescence. Besides, the energies involved are 10^{-3} times smaller than the typical energies of the galactic masers. Thus, this local phenomenon is not the long-sought optical-infrared analog of the powerful, high-gain astrophysical masers.

Looking for an object that could help solve this 30-year puzzle of why astrophysical masers are observed and lasers are not, we chose MWC 349A. This luminous star, ≈ 30,000 L, (10), is surrounded by a massive ionized envelope that has been detected in more than 20 hydrogen emission α lines—from the visual H2α line (11) at 0.65 μm to the radio H92α line (12) at 3 cm. (Hα denotes the hydrogen transition between the levels with principal quantum numbers n and n + 1.) Several of the α lines in the millimeter domain were found to have a peculiar velocity structure: two intense, narrow spectral peaks superimposed on a broad component similar to that found for other transitions (13). The narrowness and the high intensity of the double-peaked component have been attributed to masers (13). The double-peaked component first appears at H16α (2.2 mm) and is seen down to H21α (0.45 mm)—the shortest wavelength submillimeter α line observable from the ground (2, 13–16). Yet the optical and near-infrared α lines show no sign of lasing (17). Thus, MWC 349A was a promising candidate for detecting the first high-gain astrophysical lasers in the far-infrared domain and for studying the transition from the apparently amplified long-wavelength lines to the apparently nonamplified short-wavelength lines. The latter could shed light on the puzzle of the lack of observed lasers in general.

We observed the H110α line at 52.5 μm on 15 June 1994 and the H12α and H15α lines at 88.8 and 169.4 μm on 16 August 1995 with the 91-cm telescope of the Kuiper Airborne Observatory (KAO), using the facility’s cryogenic grating spectrometer (18, 19). Spectral resolutions were ≈ 80, 80, and 140 km s\(^{-1}\), respectively, and the measured fluxes were 36 ± 13 × 10^{-20}, 5.5 ± 2.5 × 10^{-20}, and 8.1 ± 1.9 × 10^{-20} W cm\(^{-2}\) km\(^{-1}\), respectively. The H12α measurement is slightly above 2σ and is formally only an upper limit. The H10α line is measured to nearly 3σ and is a probable detection (20). The H15α line is more than 4σ and is clearly a solid detection (Fig. 1). The fact that all three lines are observed to fall within one-quarter channel of their expected wavelengths, which is well within our calibration uncertainty of ±0.5 channels, increases confidence in these results. No other atomic or molecular features of any significant strength are expected in any of these bandwidths.

A convincing case for lasing in the newly detected lines can be made by comparing their fluxes with those at other wavelengths and using simple phenomenological arguments concerning the nature of the emission. The nonmasing parts of MWC 349A’s envelope radiate spontaneous emission in the α lines, which is partially reabsorbed by the free electrons...
moving in the electric field of the free protons. The fluxes in the lines formed in this way are predicted to decrease with increasing $n$ according to a power law whose index varies from approximately $-6$ to $-7$ at the smallest $n$ to approximately $-8$ at $n \approx 40$ (17). Figure 2 compares the observed fluxes with the simplest spontaneous emission model—a power law with a constant "intermediate" value of the power index of $-7$. The residual deviations from the model are remarkably small for two groups of lines: the optical—near-infrared lines [including the recently detected H7α at 19 μm (21)] and the radio lines. These lines embrace, in total, almost 5 decades in wavelength and almost 12 decades in intensity. This convincingly demonstrates that all these lines (except, perhaps, H41α) are due to spontaneous emission. In contrast, the millimeter and submillimeter lines form a prominent "hump" above the interpolated level of spontaneous emission, which confirms that they are amplified by masing.

The newly detected infrared lines also show excess radiation above the predicted spontaneous level. HIα and H12α were measured 14 months apart, and the nonmonotonic behavior of their excesses may result from variability that is similar to that observed for the masers in this source (14, 22). For both lines, the excess is smaller than for H15α, which corroborates the suggestion (20) that observable lasing in MWC 349A vanishes somewhere near $n \approx 10$. We emphasize that the qualitative conclusion about a strong (more than an order of magnitude) excess in H15α does not change with the slight variations of the model power index [several models were tried; see, for example, (17)]. This result is based on the collective properties of a large number of lines, whence its robustness.

The detection of lasing in these lines proves that population inversions persist in the ionized recombining hydrogen down to at least $n \approx 10$ to 15, at densities as high as $\approx 10^6$ cm$^{-3}$. This is in accordance with the population calculations (23) and demonstrates a basic understanding of the numerous fundamental quantum-mechanical processes controlling hydrogen populations at high densities.

It is easy to explain why detectable amplification turns on near $n \approx 40$. Past observations have revealed two morphological components in the envelope of MWC 349A: (i) an ionized outflow at $\approx 50$ km s$^{-1}$ (24) and (ii) a circumstellar gas-dust disk (Fig. 3). Each line has an optimum gas density at which its amplification per unit length is maximum; the lower the $n$, the higher the optimum density. Recalling that the density in the disk is proportional to $R^{-2}$, where $R$ is the distance from the center, the lower the $n$ of an $\alpha$ line, the smaller should be its masing (or lasing) ring. Calculations show (17) that gains are less than unity for the lines arising from $n \approx 40$, in the peripheral part of the disk, and explain why only spontaneous emission is observed. For $n \lesssim 36$ to 40, the gain along the ring chords first surpasses unity and then rises toward smaller $n$. This occurs even though the ring radius is decreasing—because of the strong dependence of the gain.
on density—and gives rise to the strongly amplified lines making theump shown in Fig. 2.

The more intriguing question is why does laser apparently vanish at $n \approx 10^5$? At the moment, there are three possible explanations. (i) There is the possibility (15) that the disk only extends down to $R \approx 40$ astronomical units (AU), where its ionized density is $\approx 10^{-3}$ to $10^{-4}$ cm$^{-3}$, which is the optimum for amplification of the lines with $n \approx 20$. Because the lines with lower $n$ require progressively higher densities, the intensity generated in this innermost ring decreases with decreasing $n$. It is estimated (20) that in this case laser becomes undetectable near $n = 10$. (ii) If we assume that the disk continues inward of $40$ AU and that each lasing line forms at its optimum density, then it can be shown (17) that for $n \approx 30$ the amplification "saturates," which slows the increase of intensity with decreasing $n$. Furthermore, the size of the lasing hot spot decreases with decreasing $n$ (Fig. 3), so that the flux due to spontaneous emission, which arises from the source as a whole, becomes increasingly dominant, and at $n = 10$ the lasing component becomes undetectable on this bright spontaneous-background. If this is the case, intra-disk interferometers will detect small (0.1 to 0.2 arc sec) bright hot spots lasing in the near-infrared hydrogen lines in the inner disk. (iii) It is also predicted in the latter model that the laser solid angle $\Omega$ increases with $n$ as $\Omega \propto n^{-4}$. If the disk is tilted slightly from our line of sight, this would remove the low-$n$ lasers from our view first. Future observations should help choose between these (and perhaps other) possibilities. Hypothesis (ii)—the competition between the laser and the spontaneous-emission—may provide a clue for understanding the general lack of observed astrophysical lasers.

The brightness temperature ($T_B$) and amplification of these lasers can be calculated once their angular sizes are known. To get a rough estimate, we assume that the disk continues inward of $40$ AU and that $115_\mu m$ forms in the disk at its optimum density of $N_\mathrm{H} = 1 \times 10^4$ cm$^{-2}$, which occurs in the model at a radial distance $r \approx 5$ AU from the star (17). We also assume that $115_\mu m$ is a single-peaked line—any narrow double-peaked component will have an even higher brightness temperature. Taking $r$ as an upper limit to the linear scale of the laser’s hot spot and assuming a line width $\Delta v = 78$ km s$^{-1}$ (2), we obtain $T_B \approx (k \cdot F)^2/(2k \cdot \Delta v) \approx 10^7$ K, where $k$ is the wavelength, $F$ is the observed integrated flux, and $D$ is the distance to the star $r = 1200$ pc (10). If the input radiation temperature of the laser is equal to the typical physical temperature of the gas in an HII region ($\approx 10^4$ K), then the amplification factor $A \approx 10^5$. Similar values of $T_B$ and $A$ are estimated for the H10x lines. Thus, these far-infrared lasers may be rather strong amplifiers, with amplification factors and brightness temperatures comparable to or greater than those for the millimeter masers in this source (22). Whereas the amplification in hydrogen is expected to limit gains and brightness temperatures to less dramatic values than those for the strongest molecular masers (17), the estimated luminosities in the lasing hydrogen lines, $\approx 0.01$ to $0.1$ Jy, are comparable to those of the strongest galactic molecular masers (25).

Detection of these new lines was due to their lasing, because purely spontaneous lines would be below our KAO detection thresholds. Observations with higher signal-to-noise ratios and improved spectral resolution ($\approx 10$ km s$^{-1}$) are still desirable. The Infrared Satellite Observatory will hopefully provide higher signal-to-noise flux measurements for all the lines in the far infrared. The Stratospheric Observatory for Infrared Astronomy (26) will have sufficient spectral resolution to observe any double-peaked velocity structure, enabling us to precisely localize the lasers in the Keplerian disk and thereby ascertain whether the disk has a void inward of $R \approx 40$ AU, which is important for understanding planet formation in such disks (27).

REFERENCES AND NOTES