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ITHACA, N. Y.

CRSR 775

MOLECULAR HYDROGEN EMISSION FROM W51

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September 1981

(NASA-CR-164608) MOLECULAR HYDROGEN EMISSION FROM W51 (Cornell Univ., Ithaca, N. Y.) 17 p HC A02/MF A01 CSCL 03B

N81-33117

Unclas
G3/93 27444

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Received: 1981 June 12

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ABSTRACT

We have detected emission from the v = 1 → 0 S(1) quadrupole transition of H_2 toward the cluster of intense infrared and H_2O maser sources in W51 (North). The apparent luminosity of this line in W51 (North) is only about 4% of the luminosity of the same line toward the Kleinmann-Low infrared cluster in Orion; however, additional line-of-sight extinction and spatial extent of the source may account for the lower apparent power in W51. Genzel et al. (1981) have suggested that the infrared and H_2O properties of these clusters are quite similar. We discuss the implications of the H_2 emission for mass loss in the W51 region and briefly consider some recently proposed models of radiation-driven mass outflow from pre-main sequence stars.

Subject headings: interstellar: molecules - infrared: spectra - nebulae: individual - shock waves

I. INTRODUCTION

The region W51 (North) contains a cluster of infrared, radio continuum, and H_2O maser sources embedded in a molecular cloud at a distance of 7 kpc. Genzel *et al.* (1981) have emphasized the similarity between the infrared and radio properties of this cluster and the Orion Nebula and associated Kleinmann-Low infrared cluster, which is often considered to be the prototype of a region of star formation. An unusual property of Orion is the intense emission from molecular hydrogen first observed by Gautier *et al.* (1976) and subsequently by a variety of other observers (see, e.g., Beckwith 1981 for a review). Here we report the detection of H_2 emission from W51 (North) and briefly compare its properties with the H_2 emission in Orion.

II. OBSERVATIONS

The observations were made with the 3-meter NASA Infrared Telescope Facility (IRTF) at Mauna Kea, Hawaii, together with the Cornell University grating spectrometer described by Beckwith *et al*. (1982). A CaF_2 lens in front of the entrance window of the spectrometer converted the f/35 focal ratio of the IRTF to the f/16 focal ratio of the spectrometer optics. For these observations, the spectral resolution was 0.0025 μm at the 2.122 μm wavelength of the $v = 1 \rightarrow 0$ S(1) line, and the beam size was $5'' \times 6''$ ($\alpha \times \delta$). The telescope tracking was generally good to $2''$ during the ∿10 minutes required to complete a wavelength scan across the H_2 line. Sky subtraction was accomplished by chopping $38''$ at 10 Hz in the east-west direction. The noise equivalent flux density was 85 mJy $Hz^{-1/2}$.

Measurements of the standard stars σ Cyg and ν Peg, whose intrinsic 2.1 μm flux densities were assumed to be 20.1 and 41.3 Jy respectively, were used to set the flux density scale. There was no evidence for extinction due to the Earth's atmosphere in the spectra of the standard stars and no corrections have been applied to the data. Observations of the $v = 1 \rightarrow 0$ S(1) line in NGC 7027 immediately following the W51 observations established both the wavelength scale and spectral resolution. Lines from an argon lamp measured at various times during the observing run verified the wavelength scale. We estimate the uncertainty in the flux density scale to be less than 10% and the uncertainty in the wavelength scale to be of order 0.0003 μm.

Figure 1 displays the measurements toward W51 IRS2 EAST 8 μm (notation of Genzel et al., 1981). The instrumental profile was fit to the data points by varying the amplitude and central wavelength of the profile to minimize the Chi-square of the residuals as described by Beckwith et al. (1982); the width of the profile was fixed at the value found from the observations of NGC 7027. The line strength is 30 ± 4mJy. The underlying continuum flux density is 150 mJy in reasonable agreement with the value given for IRS2 EAST in Figure 3 of Genzel et al. (1981).

One or two scans each were made at positions offset by ±6" in both right ascension and declination. These data are insufficient to limit the total extent of the S(1) emission with any certainty, although we would have detected any emission more intense than that seen at the central position. The continuum flux 6" west of the central position is 100 mJy in agreement with a contribution from the HII region IRS2 WEST seen by Genzel et al. (1981). A more complete characterization of the H_2 emission region was precluded by limited observing time.

III. LUMINOSITY AND EXCITATION

The apparent S(1) line flux from W51 is 6.2×10^{-14} erg $s^{-1}cm^{-2}$. If the distance to W51 is 7 kpc (Genzel et al. 1981), then the luminosity in the line is $\sim$0.1 $L_{\odot}$. This value is a lower limit, since there may be extinction at the line wavelength (2.12 μm), and the angular extent of the line emission region may be larger than the 5" beam. Estimates of the extinction toward IRS2 WEST and IRS2 EAST are very uncertain, but 2 to 3 magnitude at 2 μm is possible within W51 itself. Since the line-of-sight distance to W51 is 7 kpc through the plane of the galaxy, there could easily be an additional 2 to 3 magnitudes of interstellar extinction. For comparison, there are approximately 3 magnitudes of extinction at 2.2 μm along the 10 kpc path to the galactic center (Becklin et al. 1978). If 5 magnitudes of total extinction is appropriate for the H_2 emission, then the S(1) line luminosity is at least 10 $L_{\odot}$. Note that the extinction corrected luminosity of the S(1) line in Orion is of order 20 $L_{\odot}$ (Beckwith et al. 1982).

We cannot estimate the size of the emitting region with any certainty as discussed above, but we note that if Orion were at the distance of W51, the H_2 emission region mapped by Beckwith et al. (1978) would be slightly smaller than 5" in extent. The 5" spatial resolution also covers the total extent of the high-velocity water masers measured by Genzel et al. (1981). There are, however, H_2 emission regions such as DR21 and NGC 7538 which would be much more extended than 5" at the distance of W51 (Fischer et al. 1980; Fischer, Righini-Cohen and Simon 1980). If the H_2 in W51 is as extended as the largest-known H_2 emission region, it would increase the S(1) luminosity by more than an order of magnitude. Considering these uncertainties, the luminosity given here must be regarded only as a lower limit. If the extinction is large or the source is somewhat more extended than 5", the H_2 luminosity could be comparable to that in Orion.

It is impossible to determine the excitation temperature of the H_2 from our data, since only one line has been measured. Both radiative pumping in the ultraviolet Lyman and Werner bands (Black and Dalgarno, 1976) and collisional excitation in a hot gas have been suggested for the excitation of interstellar molecular hydrogen. The intensity of the $v = 2 \rightarrow 1$ S(1) line provides a discriminant between these two cases (e.g., Beckwith et al., 1978), but the line would be difficult to measure in W51 with available instruments, even in the most optimistic case. No H_2 emission source is known to be radiatively pumped, whereas, several (most notably Orion) are probably collisionally excited. We will assume in what follows that the H_2 is collisionally excited in a hot gas, most likely behind a strong molecular shock (Hollenbach and McKee 1979).

IV. DISCUSSION

The apparent luminosity of the S(1) line in W51 is only 0.1 $L_\odot$, This line has an apparent luminosity of 2.5 $L_\odot$ in Orion. On the other hand, the total radiative luminosity of W51 is of order a few times 10^6 $L_\odot$ (Genzel et al., 1981) approximately ten times the 2×10^5 $L_\odot$ of Orion (Werner et al., 1976). Genzel et al. have emphasized the similar infrared properties of the two sources. If the molecular hydrogen emission is indicative of the amount of power liberated through mass motions within a source, then W51 may have a very small amount of mass motion for its luminosity compared to Orion.

The relative mass motion cannot be established with certainty until the relative amounts of 2 μm extinction along the lines of sight to the S(1) emitting regions in W51 and in Orion, and the full spatial extent of the S(1) emitting region in W51 are measured. Unless radiation pressure drives the mass motions, as in the models discussed below, there will not necessarily be a direct correlation between bolometric luminosity (L) and S(1) luminosity (L_H). That there exists at least an indirect correlation seems likely because the maximum ratio L_H/L that has been observed in pre-main sequence objects appears to be roughly constant over a range of four orders of magnitude in L (see the Table in Zuckerman, 1981). Nonetheless, in the following discussion we assume that W51 and Orion do differ significantly in the sense that L_H/L is much smaller in W51. Most of the arguments presented are germane even if the H_2 luminosity in W51 is much greater than derived above.

The different ratio of the H_2 to total luminosity might result from three possibilities: the source of mass motions is much different in W51 than in Orion; the source of mass motions in W51 is similar to that in Orion but comes from a low luminosity object; or the mass motions are transient phenomena, and we are observing a relatively quiescent phase in W51. As regards the first possibility, the H_2 emission in W51 could be produced by simple expansion of the HII region associated with IRS2 or by direct radiation pressure on dust grains around the most luminous object. Using the radio measurements of Scott (1978) for the size and electron density of IRS2 WEST, assuming a molecular density of $2\times10^4\,cm^{-3}$, which is the same as the peak electron density, and speed of 10 km s^{-1} for the shock wave, and using the calculations of Kwan (1977), we expect an H_2 luminosity of 0.1 $L_\odot$ in a $\hat{5''}$ beam. A pressure 6×10^{-8} dyne cm^{-2} will drive this shock wave into the surrounding medium. This pressure is available from single absorption of photons around a $10^6 L_\odot$ object. The pressure, $L/(4\pi r^2 c)$, is equal to 2×10^{-7} dyne cm^{-2} at a distance of 2.5×10^{17} cm ($\approx2''.5$). Either of these processes, both of which fail by large factors in Orion, may therefore plausibly account for the H_2 emission from W51.

If, on the other hand, the H_2 emission in W51 is caused by a process similar to the Orion emission, then it is relatively weak compared with the total luminosity of the region. A relatively low luminosity object may drive the outflow in W51, or the mass motions may be time-variable and at a relatively quiet phase. Attempts to match the observed slope of the high-velocity CO emission intensity in KL versus radial velocity with stationary outflow models have been unsuccessful (Kuiper et al. 1981; Phillips and Beckman 1980). A model for transient, radiatively-driven mass loss around much lower luminosity stars has been proposed recently by Beichman and Harris (1981). Following the suggestions of Herbig (1977) and Larson (1980) that T Tauri stars of luminosities $\sim 10\ L_\odot$ recurrently flare to luminosities $\sim 10^3\ L_\odot$ (the FU Ori phenomenon) Beichman and Harris suggested that such flares can radiatively drive very large mass motions (see also Dopita 1978). Thus, in Orion or W51, the infrared sources may now be in a quiescent, low-luminosity phase. The high-velocity CO, shocked-molecular hydrogen, high-velocity H_2O masers, and Herbig-Haro objects that are sometimes seen in the vicinity of these sources could have been accelerated during a preceding phase of high stellar luminosity. This model is appealing in many respects, but there are several arguments that must be countered if it is to be considered viable.

Of the three best known FU Orionis-type objects V1057 Cyg, V1515 Cyg and FU Ori, none is associated with any signposts of strong stellar winds, henceforth called HV sources. Since the time between flares, characteristically $10^3 - 10^4$ years, is also the lifetime that characterizes the HV sources, one expects to see some signposts. Furthermore, flares to $>10^7\ L_\odot$ are necessary in this model to explain HV sources like Orion KL, and there is no observational evidence for individual pre-main sequence stars with such large luminosities. [The very luminous, massive stars postulated to excite η Carina and 30 Doradus appear to be different sorts of objects (Andreisse et al. 1978, Casinelli et al. 1980)]. Finally, since the underlying cause of the recurring flares is uncertain (Dopita 1978; Herbig 1977, Larson 1980), the underlying source of energy for the HV phenomenon must still be explained.

Phillips and Beckman (1980) discuss a model to explain the largest luminosity HV sources such as Orion KL. Solomon, Huguenin, and Scoville (1981) also consider this an attractive model for Orion. As was originally pointed out by Faulkner (1970) in the context of radiative acceleration of planetary nebulae, via electron scattering, if radiation is multiply scattered or absorbed and re-radiated, then momentum rates substantially in excess of L/c may be transferred from the radiation field to the envelope. Phillips and Beckman (1980) assume that dust can provide an appropriate scattering medium and derive a terminal outflow velocity of 75 km s^{-1} near an object of 1.5×10^5 $L_\odot$. This velocity is similar to that observed by Nadeau and Geballe (1979) for the H_2 emission and by Zuckerman, Kuiper, and Rodriguez-Kuiper (1976) for the $J = 1 \to 0$ CO emission in KL. This model is attractive for its simplicity, but has a variety of potential limitations.

A difficulty with radiative models is that the rate of momentum input to the wind ($\dot{M}v$) is observed to be greater than the rate of momentum supplied from photons (L/c) by a factor of order 100 (Zuckerman 1981). To produce an overpressure ratio (defined by Zuckerman as $\dot{M}vc/L$) of order 100, radiation must be scattered or absorbed and re-radiated of order 100 times (Salpeter 1974), so the dust albedo must be almost 1, or the dust optical depth for absorption must be of order 1 at the photon wavelength typical of the one-hundredth absorption and re-radiation. Phillips and Beckman assume dust temperatures near 1000 K, so the optical depth at a few microns must be of order 100 to trap the radiation sufficiently. A normal reddening curve (e.g., Becklin et al. 1978) implies a visual optical depth of order 1000 which is large in comparison to estimates of the visual extinctions to the known infrared sources in the KL cluster (Downes et al. 1981; Aitken et al. 1981). For the high-luminosity HV sources, this argument is weak because objects with such large extinctions would probably not have been detected by existing surveys, and the CO, H_2, or H_2O emission which characterizes mass outflow is usually too extended spatially to define the precise center of expansion.

The stars T Tauri and HH29IR present much stronger cases against such large optical depths. At a distance of 160 pc, the total luminosity of T Tauri is 20 $L_\odot$ (Harvey et al. 1979). Bertout (1980) derives a color excess B-V of 0.9 magnitudes based on data from 1400Å to 11 cm, implying a total visual optical depth, which includes both circumstellar and interstellar extinction, of order 3. The observed visual magnitude of the star (Cohen 1973) relative to its total luminosity is consistent with this optical depth and with the shallow 10 μm silicate absorption feature (Simon and Dyck 1977) implying a very small optical depth in the infrared continuum. Yet the 2 μm H_2 emission observed by Beckwith, Gatley, and Persson (1978) suggests an overpressure ratio of order 20. HH29IR presents an even more extreme discrepancy. The silicate feature and the infrared colors suggest a modest visual optical depth, probably less than 10 (Beichman and Harris 1981), whereas, the CO model of Snell, Loren, and Plambeck (1980) and the total luminosity of ~30 $L_\odot$ from Beichman and Harris imply an overpressure ratio of order 1000. In contrast to the pre-mainsequence stars, post-main-sequence infrared stars with large mass-loss rates such as IRC-10216, CRL 2688, and the OH/IR stars observed by Werner et al. (1980) have visual optical depths greater than 15 (Cohen 1979) and deep 10 μm silicate features (Evans and Beckwith 1976), but the overpressure ratios are of order 1 (Zuckerman 1981) as expected for simple radiatively driven mass loss.

More exotic models for the mass-loss phenomena are already suggested by the anisotropies observed in several of the HV sources. Snell, Loren, and Plambeck (1980) present the clearest evidence for these flows through their CO observations in L1551. The mass loss appears to occur in two oppositely directed jets which the authors suggest are confined by an accretion disk around HH29IR. Rodrigues, Ho, and Moran (1980) show a similar phenomenon occurs in Ceph A but with the luminosity greater by a factor of 1000. Even though W51 could power its H_2 emission by much less exotic means, we believe it is probably similar to these other sources of mass loss. This conclusion is based more on the similarities of the infrared and molecular properties than the H_2 emission.

Finally, the mass loss phenomena in the HV sources discussed above is characterized by lifetimes of order 10^4 years. This time is much shorter than either the expected lifetime of subgroups within clouds $\sim 10^6$ years (Sargent 1979) or the lifetime of the stars. The many examples of these HV sources suggest that mass loss recurs several times per subgroup. It is therefore possible that W51 represents a stage at which the mass-loss rate is not at its peak.

ACKNOWLEDGEMENTS

We are grateful to E. E. Becklin for suggesting W51 as a potential source of H_2 emission. D. A. Thompson and C. Telesco provided support for this experiment at the telescope without which these observations would not have been possible. G. Gull, J. Houck, and J. Wyant gave us valuable assistance during the construction of the instrument, and K. Matthews provided useful advice about the InSb detector and preamplifier electronics. We profited from discussions with E. Becklin, D. Downes, and D. Jaffee during preparation of the paper.

The instrument was constructed with funds from a Cottrell Research Grant to Cornell University from the Research Corporation. This research was supported in part by NASA Grant NSG 2412 to Cornell University and by NSF Grant AST-76-17600 to the University of Maryland.

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FIGURE CAPTION

Figure 1 - The measurements of the v = 1→0 S(1) line of molecular hydrogen toward W51 (North). The solid line is a least squares fit of the instrumental profile function to the data as described in the text.

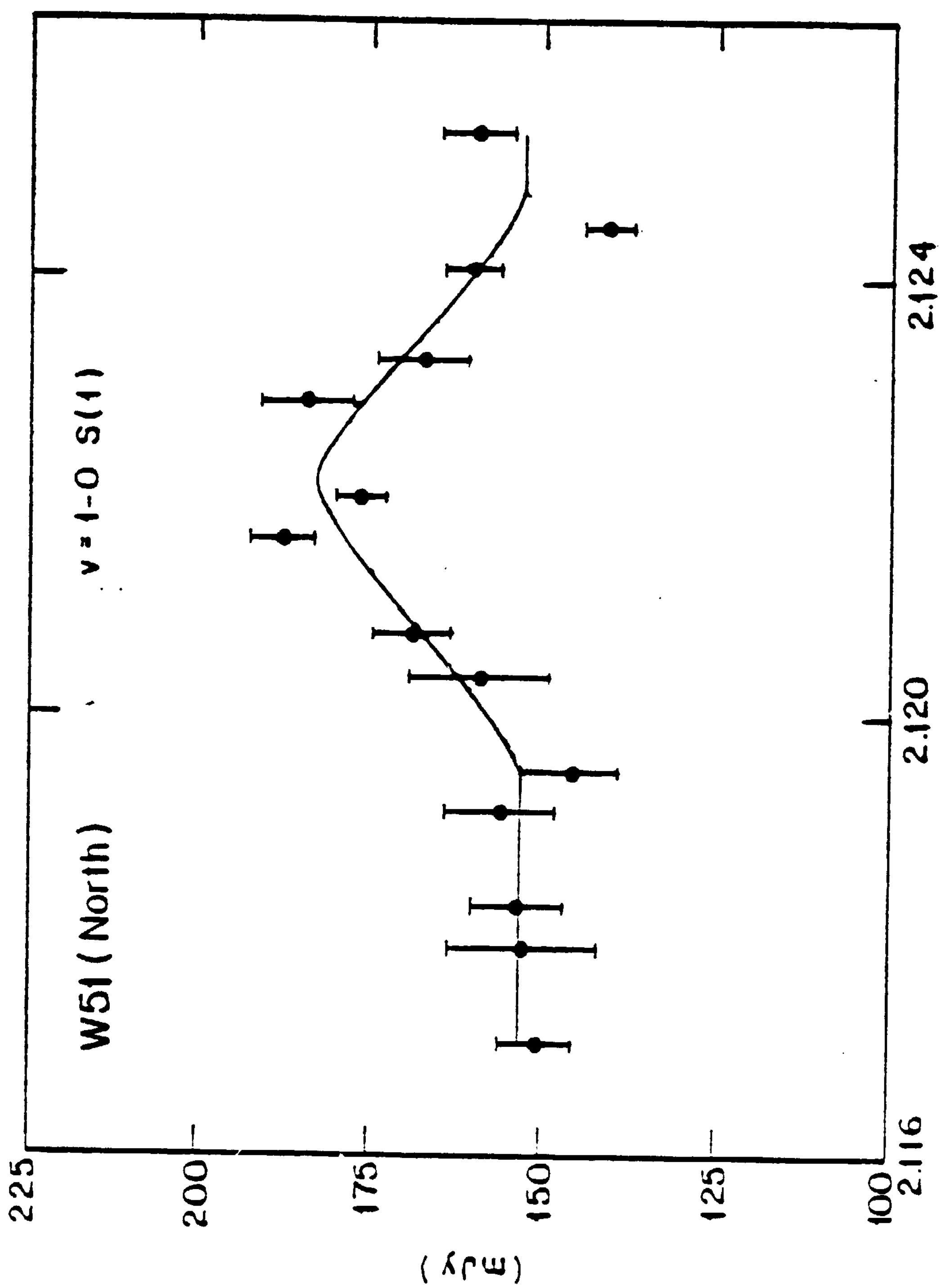

Figure 1

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