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LUMINOUS MOLECULAR HYDROGEN EMISSION IN THE GALAXY SYSTEM NGC 3690–IC 694

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ABSTRACT

We report the detection of line emission of vibrationally excited H_2 from the galaxy system NGC 3690–IC 694. The line emission is distributed within the system. The total observed luminosity in the H_2 $v = 1$–0 $S(1)$ line alone is approximately 1.5×10^7 $L_\odot$. We also detected Brγ line emission of the system; its observed luminosity indicates that at least 4×10^{54} ionizing photons per second are required to maintain ionization of the H II. The H_2 is probably heated by shocks, and the mass of hot H_2 exceeds 2×10^4 $M_\odot$.

Subject headings: galaxies: individual — infrared: sources — infrared: spectra — stars: formation

I. INTRODUCTION

The optical appearance of the NGC 3690–IC 694 system[5] suggests an interaction of two galaxies (de Vaucouleurs and de Vaucouleurs 1967). These authors measured the radial velocities of NGC 3690 and IC 694 as 3104 km s^{-1} and 3220 km s^{-1} respectively; for a Hubble constant of 75 km s^{-1} Mpc^{-1}, the distance to the system is 42 Mpc. Spectroscopically, the system appears to be a giant and very luminous H II region (Weedman 1972; Sargent 1972; French 1980). It is a radio source and an infrared source with an upturned spectrum in the far-infrared (Sramek and Tovmassian 1976; Rieke and Low 1972; Joyce and Simon 1976). From their optical, infrared, and radio continuum observations, Gehrz, Sramek, and Weedman (1983) conclude that the system contains several sites of vigorous star formation activity. They argue that the current episode of star formation has produced more than 10^9 $M_\odot$ in massive stars that produce several supernovae per year. CO observations show that the system contains a remarkably large mass of molecular hydrogen, $M(H_2) \sim 10^{10} M_\odot$ (Solomon, deZafra, and Barrett 1983).

In our Galaxy, emission of vibrationally excited H_2 is associated with star-forming regions and also with supernova remnants. Excitation of the H_2 is thought to be by shocks (see Shull and Beckwith 1982 for a review). Interacting galaxy systems are often associated with starbursts (Larson and Tinsley 1978). Shocks generated in the disks of such galaxies, possibly the mediators of these starbursts, could also excite H_2. The hydrogen Brackett lines are a useful probe of heavily obscured H II regions. Thus, to understand the activity and physical conditions in the remarkable NGC 3690–IC 694 system, we have carried out observations of the $v = 1$–0 H_2 line emission and Brackett-line emission and describe our results in this *Letter*.

II. OBSERVATIONAL RESULTS

Observations in the 2.0–2.5 μm spectral region were obtained using circular variable filter-wheel (CVF) spectrometers at the 2.1 m and 1.3 m telescopes of Kitt Peak National Observatory (KPNO) in 1982 June and 1983 January respectively. The resolution of the spectrometer used at the 2.1 m telescope is $\lambda/\Delta\lambda \sim 77$. With this instrument, the Brγ (2.166 μm) and H_2 $v = 1$–0 $S(1)$ (2.122 μm) lines are just barely separated. At the 2.1 m telescope, a 21".4 aperture was used with a 90" E-W chopper throw. The position of this observation and the measured spectrum are plotted in Figures 1*a* and 1*b*. Emission of the H_2 $v = 1$–0 $S(1)$ line and the H Brγ line is clearly evident although the lines are blended. The intrinsic line widths are likely to be much less than the CVF resolution. Thus line fluxes were calculated by multiplying the peak flux density in the line by the line width set by the CVF resolution and are listed in Table 1.

At the 1.3 m telescope, a 34" aperture was used with a chopper throw of 1' N-S. The spectrometer resolving power is $\lambda/\Delta\lambda \sim 77$ for observation of a point source. However, the resolution of this instrument is degraded in large-aperture observations of extended sources and depends on the source intensity distribution. Ideally, the resolution should be measured by observation of an isolated spectral line. The presence of both Brγ and $S(1)$ line emission from NGC 3690–IC 694 made this impossible. We therefore estimate the resolving power to be $\lambda/\Delta\lambda \sim 50$ on the basis of our measurement during 34"

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[5]The system is also identified as Markarian 171 and shown as object no. 299 in the *Atlas of Peculiar Galaxies* (Arp 1966).

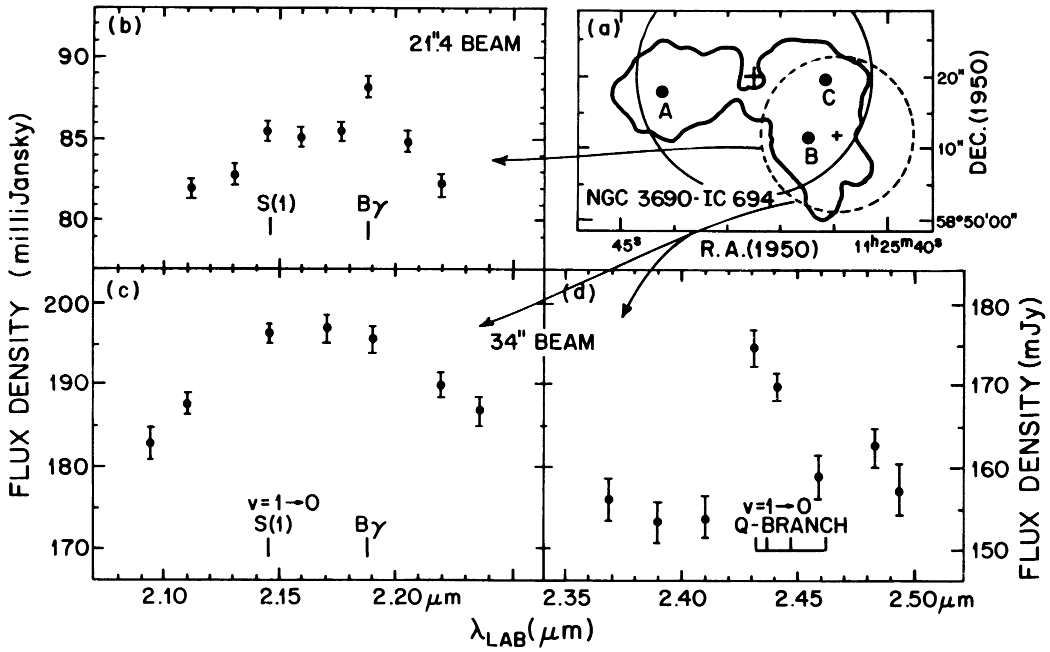

FIG. 1.—(a) The positions of the 21".4 and 34" beam observations are marked by plus signs. The circles represent the beam diameters. Also plotted are the lowest 10 μm contour level from the map of Gehrz, Sramek, and Weedman (1983) and the peaks of 10 μm emission, designated A, B, C. Peak A is located within IC 694, and peaks B and C are within NGC 3690. (b) The spectrum obtained with the 21".4 beam plotted as a function of laboratory wavelength. The wavelengths of the H_2 v = 1–0 $S(1)$ and H Brγ lines are plotted at their redshifted values for v_r = 3150 km s^{-1}. The resolving power of this observation is λΔλ = 77. (c) The spectrum of the $S(1)$ and Brγ emission obtained with the 34" beam at an estimated resolving power λ/Δλ ~ 50. (d) Same as (c) but for the v = 1–0 Q-branch emission.

aperture observations of the extended emission of the H_2 v = 1–0 $S(1)$ line from the DR 21 region (Fischer, Righini-Cohen, and Simon 1980). We observed the Brγ, v = 1–0 $S(1)$, and Q-branch lines at the position indicated in Figure 1a and show the spectra in Figures 1c and 1d. At the resolution of these observations, the Brγ and $S(1)$ lines are severely blended, and the individual lines of the Q-branch cannot be resolved. Thus, measurement of line emission of the blended Q-branch at approximately 2.41 μm is useful principally to confirm the detection of vibrationally excited H_2 (see Fischer *et al.* for examples of observations of galactic sources). The Brγ and $S(1)$ line fluxes were calculated using λ/Δλ ~ 50 and are listed in Table 1.

Figures 1c and 1d show that the continuum measured with the 34" beam at λ ~ 2.4 μm is about 15% lower than at λ ~ 2.1 μm. The broad-band spectra measured with smaller beams by Gehrz, Sramek, and Weedman (1983) and Joyce and Simon (1976) suggest a flattening of the spectrum in this wavelength region. The decrease we measured is surprising, however. We regard it as uncertain because of the difficulty of flux calibration in the 2.4–2.5 μm wavelength region where absorption by terrestrial H_2O can be important. If subsequent observations verify the depressed flux shortward of 2.41 μm, it could be attributable to CO overtone absorption in the atmospheres of late-type giants and supergiants (Frogel *et al.* 1978; Wynn-Williams *et al.* 1979).

TABLE 1

OBSERVED LINE FLUXES AND LUMINOSITIES

R.A.(1950)	Decl.(1950)	Beam Size	Spectral Line	Measured Flux (10^{-20} W cm^{-2})	Luminosity[a] (10^7 $L_\odot$)
$11^h25^m42^s.5$ ...	58°50'20"	34"	H_2 v = 1–0 $S(1)$	2.9 ± 0.4	1.5
			H Brγ	2.6 ± 0.5	1.4
			H_2 v = 1–0 Q-branch	3.9 ± 0.6	2.0
11 25 40.9 ...	58 50 12	21".4	H_2 v = 1–0 $S(1)$	0.64 ± 0.13	0.3
			Brγ	1.01 ± 0.13	0.5

[a]Calculated from line flux uncorrected for extinction and assuming 42 Mpc distance for H = 75 km s^{-1} Mpc^{-1}.

III. DISCUSSION

The line fluxes measured with the 21″ and 34″ beams (Table 1) indicate that the Brγ and $S(1)$ line sources are not entirely contained in the smaller beam, but it is not possible to specify whether the sources are extended or concentrated at two or more emission regions. If the Brγ and $S(1)$ line emission is radiated principally at the 10 μm emission peaks identified as A, B, and C by Gehrz, Sramek, and Weedman (1983), then our observations imply that the Brγ and $S(1)$ lines are about 2 and 3 times stronger, respectively, at peak A than at peaks B and C combined. Gehrz *et al.* find that Hα and Hβ are stronger at B and C than at A. This suggests that the peak A region may be heavily obscured.

Since the 34″ beam observations included the entire complex of radio and infrared sources (Fig. 1*a*), these $S(1)$ and Brγ line fluxes probably represent the total output of the system in these lines. At the distance of 42 Mpc, the total luminosities of the $S(1)$ and Brγ lines, uncorrected for extinction, are $1.5 \times 10^7\ L_\odot$ and $1.4 \times 10^7\ L_\odot$.

The observed $S(1)$ line luminosity exceeds that of the Orion source (also before extinction correction) by a factor of almost 10^7 (75 km s^{-1} Mpc^{-1}/H)^2 and that of the NGC 1068 by a factor of 13, assuming that the galaxy distances are both given by the Hubble relation (Beckwith *et al.* 1978; Thompson, Lebovsky, and Rieke 1978; Hall *et al.* 1981). We can estimate the luminosity of all the H_2 lines, $L(H_2)$, by assuming conditions similar to that of the Orion source: that the H_2 lines are optically thin and that the energy levels are populated thermally at an average temperature of approximately 2000 K (Scoville *et al.* 1982). With these assumptions, we derive $L(H_2) > 1.5 \times 10^8\ L_\odot$ and a total mass of *hot* H_2 greater than $2 \times 10^4\ M_\odot$. These estimates are lower bounds because no correction for extinction was applied.

The optical emission-line spectrum of NGC 3690–IC 694 is like that of an H II region (French 1980). Thus its Brγ line emission probably is attributable to recombination in H II photoionized by the Lyman-continuum flux of massive stars. For Menzel case B, at $T \sim 10^4$ K, one Brγ photon will be emitted in the radiative cascade per about 77 photoionizations (Brocklehurst 1971; Giles 1977). The Brγ luminosity indicates therefore an ionizing photon flux $Q \geq 4 \times 10^{54}$ s^{-1} (again a lower bound because no extinction correction was applied). Gehrz, Sramek, and Weedman (1983) derived from their optical spectral line data the estimate $Q \sim 1.8 \times 10^{54}$ s^{-1}. It is reasonable that our estimate is larger because our observation sampled a much larger area and also because the Brγ line intensity is less sensitive than the optical lines to extinction.

Despite the high UV photon flux, the H_2 line emission probably is not powered by UV pumping. In this mechanism, photons at $\lambda \sim$ 1000–1100 Å are absorbed in lines of the Werner and Lyman bands and excite molecular fluorescence and radiative cascade; the probability that a given $v = 1$–0 transition will be involved in the cascade is 0.01–0.03 (Black and Dalgarno 1976). The observed $S(1)$ luminosity therefore implies absorption by H_2 of more than 1×10^{54} UV photons s^{-1}. We have estimated $Q \geq 4 \times 10^{54}$ s^{-1} in the entire continuum shortward of 912 Å; the actual value of Q, obtained when the extinction correction is known, is unlikely to be as much as a factor of 10 larger. We of course do not know the photon flux longward of 912 Å, but given our estimate of Q, it seems unlikely that enough photons would be available in the relatively narrow bandwidth of the Werner and Lyman band lines to drive the observed H_2 line emission. Absorption by grains will also substantially reduce the flux of available UV photons.

In view of the high star formation rate in NGC 3690–IC 694 (Gehrz, Sramek, and Weedman 1983 and below), and high mass molecular cloud gas, $m(H_2) \sim 10^{10}\ M_\odot$ (Solomon, deZafra, and Barrett 1983), it seems most likely that the H_2 line emission is radiated by H_2 heated in shocks resulting from gas flows associated with the processes of star formation. With $L(H_2) \gtrsim 10^8\ L_\odot$, and a total far-infrared luminosity $L(\mathrm{IR}) \sim 3 \times 10^{11}\ L_\odot$ (D. A. Harper, private communication), we have for NGC 3690–IC 694 that $L(H_2)/L(\mathrm{IR}) \gtrsim 3 \times 10^{-4}$. For the Orion source, using the dereddened value $L(H_2) \sim 300\ L_\odot$, $L(H_2)/L(\mathrm{IR}) \sim 1 \times 10^{-3}$ (Davis, Larson, and Smith 1982; Werner *et al.* 1976). The similarity of $L(H_2)/L(\mathrm{IR})$ in Orion and in NGC 3690–IC 694 is striking. The Orion molecular cloud is one in which both the H_2 emission and far-infrared emission are powered by activity associated with star formation. In NGC 3690–IC 694, however, both could be the composite effect of several mechanisms. For example, while the H_2 line emission could be associated with planetary nebulae and supernova remnants as well as molecular clouds, a more exotic possibility, if indeed this galaxy system is an interacting one, is that the H_2 line emission originates in shocks generated by the collision of gas clouds in the interacting galactic disks. The far-infrared emission could be the composite of diffuse galactic and molecular cloud emission. Nevertheless, the similarity of $L(H_2)/L(\mathrm{IR})$ in NGC 3690–IC 694 and in the Orion molecular cloud suggests that their H_2 emission is driven by star formation activity in similar ways.

The rate of star formation in NGC 3690–IC 694 can be estimated from the observations—either by requiring that newly formed and short-lived stars produce the ionizing flux inferred from observation, or by considering the rate at which sources of H_2 emission might be formed. If both the infrared and H_2 luminosities in NGC 3690–IC 694 arise from objects similar to the Orion source, then NGC 3690–IC 694 presently has the equivalent of 10^6 core regions of the Orion molecular cloud. Expansion time arguments for H_2 sources in our

Galaxy suggest that they are approximately 10^4 yr old (Fischer *et al.* 1983). If this is representative of the duration, τ, of the H_2 emission phase, at a level $l(H_2) \sim 300\ L_\odot$, then the formation of Orion-like H_2 sources in NGC 3690–IC 694 is $\dot{N} = 30[300\ L_\odot/l(H_2)]\ (10^4\ \text{yr}/\tau)$ stars per year. By analogy with the Orion source, this rate refers to stars in the mass range of early spectral type B stars and suggests a formation rate of 30 stars per year. This rate is about a factor of 30 greater than that of the starburst models that Gehrz, Sramek, and Weedman (1983) find give the most satisfactory fit to the required UV flux and the bolometric luminosity. They find in these models that stars in the mass range from 6 $M_\odot$ to 40 $M_\odot$ are being formed at a rate of approximately 5 $M_\odot$ yr^{-1}. The discrepancy of these star formation rate estimates is probably attributable to our lack of knowledge of the kinds of stars that are being formed in NGC 3690 and also to our incomplete knowledge of the formation, energetics, and evolution of H_2 line emission sources in our Galaxy. Critical to our estimate of $\dot{N}$ is the quantity $E(H_2) = l(H_2)\tau$, the total energy radiated in H_2 lines by a single source over its lifetime. We do not know this well for sources in our Galaxy, and it is possible that our use of the Orion source as representative is inappropriate. Alternatively, we may infer from this discrepancy that other mechanisms of shock excitation could be important. Shocks generated by the collisions of gas clouds in the possibly interacting galactic disks are obvious candidates. Survey type observations of starburst galaxies that seem to be interacting systems and those that do not should help discriminate between these possibilities.

Finally, we note that the $S(1)$ line emission of NGC 3690–IC 694 may be strong enough to permit observations that resolve its velocity structure. This offers the exciting possibility of studying the kinematics of this system and hence the nature of the interaction that is suggested by its optical appearance.

IV. SUMMARY

1. We have detected the $v = 1\text{–}0$ $S(1)$ and Q-branch lines of H_2 and the Brγ line of H from NGC 3690–IC 694.

2. Observations with two different beam sizes show that the Brγ and $S(1)$ line emission are not localized to one emission region.

3. The Brγ line luminosity, uncorrected for extinction, is $1.4 \times 10^7\ L_\odot$. Under Menzel case B conditions, a flux of ionizing photons $\geq 4 \times 10^{54}$ s^{-1} is required to balance recombination in the H II.

4. The $S(1)$ line luminosity from molecular hydrogen, uncorrected for extinction is $1.5 \times 10^7\ L_\odot$ which exceeds the comparable values of NGC 1068 and the Orion molecular cloud by factors of about 13 and 10^7 respectively.

5. The H_2 line detection implies $M(H_2) > 2 \times 10^4$ $M_\odot$ of hot ($T \sim 2000$ K) H_2. The H_2 is probably heated by shocks; UV excitation appears unlikely to be important.

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