IC 443: THE INTERACTION OF A SNR WITH A MOLECULAR CLOUD

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Abstract: Observations are presented of shocked line emission from H_2, CO and HCO+ molecules in the SNR IC 443. IC 443 is the most luminous galactic H_2 emission line source yet discovered. The implications for physical processes in shocked molecular gas are discussed.

Introduction: The SNR IC 443 is a laboratory for the study of the interaction of a shock wave with a molecular cloud. The expanding shell of the SNR is interacting with ionised, atomic and molecular gas at different positions within the remnant. Near its SE edge it is running into a dense molecular cloud, exciting molecular hydrogen line emission, as first observed by Treffers (1979). Shock-excited line emission has also been observed in CO, OH, HCN, HCO+ and CS (eg. White et al., 1987), as well as high-velocity 21cm atomic hydrogen emission (eg. Braun & Strom, 1986). This paper reports detailed observations of the molecular line emission from H_2, CO and HCO+ in IC 443. The molecular hydrogen data were obtained at the UKIRT and the CO and HCO+ data with the Nobeyama 45m radio telescope. A more complete discussion of some of these observations can be found in Burton (1986), Burton (1987) and Burton et al. (1987).

Molecular Hydrogen Observations: Figure 1 presents a map of the 1-0 S(1) H_2 line, at 2.12 μm, in IC 443. It is incomplete as the NE and central portions of Figure 1 have not yet been observed. The H_2 line emission is seen to come from several bright peaks distributed along a sinuous ridge which forms a nearly complete ring, at least 20 pc long, and lying between the two optical lobes of the source. There are over 20 resolved peaks, and the two brightest, of comparable peak flux, are located diametrically opposite each other. The total H_2 line luminosity, allowing for two magnitudes of extinction for the S(1) line and a distance to the source of 1500 pc, is estimated to be about 2000 $L_\odot$, making IC 443 the most luminous and extended galactic H_2 source

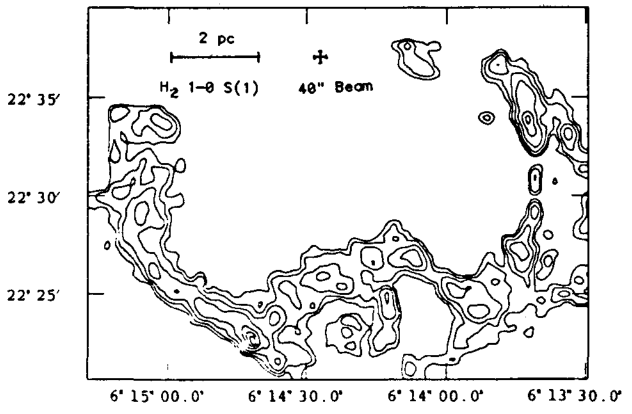

Figure 1.
1-0 S(1) line
emission in
IC 443

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yet discovered. The width of the emission ridge is unresolved in Figure 1. A 5" resolution, fully-sampled map of the peak emission region is shown in Figure 2. Although line emission is detected from all over this region, the majority of it comes from the emission ridge; the width of the ridge remains unresolved even at this higher resolution, corresponding to a spatial scale of <0.03 pc.

Figure 3 shows a spectrum in the K window of the emission from the H_2 emission peak. The emission consists entirely of H_2 lines, with negligible continuum. No Br γ recombination radiation is seen, which limits the degree of ionisation of the gas. The spectrum is typical of shock-excited sources. Measurements of the line profiles at several locations (not shown) show typical FWHM's of 20-30 km/s. The peak velocity of the emission, however, varies considerably with position (by up to 60 km/s in the positions measured).

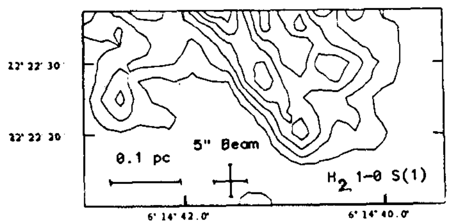

Figure 2. High Resolution (5") map of peak H_2 line emission region.

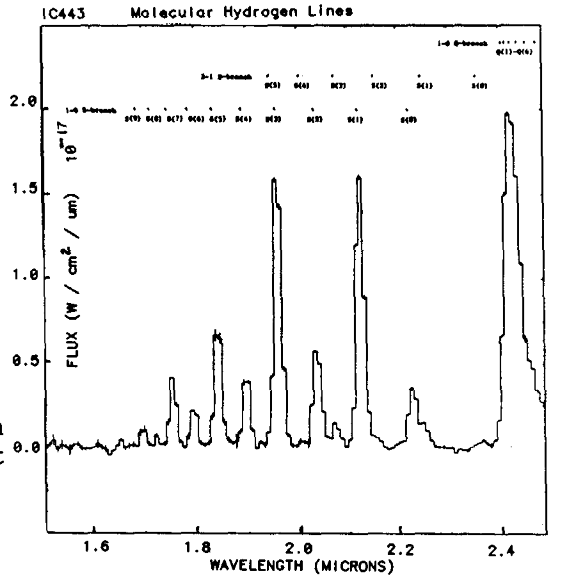

Figure 3. Spectrum through K window of the emission at the H_2 emission line peak.

<u>CO and HCO+ Observations:</u> Partial maps of CO, HCO+ and HCN (1-0) line emission (White et al. 1987) and a complete map of the 21-cm HI emission (Braun & Strom, 1986) have been published. In the regions of overlap with the H_2 map the morphology of the emission from all these species is very similar. In particular the location of the emission ridge, and the peaks along it, are coincident to the 40" resolution of the H_2 map. In Figures 4 & 5 are presented CO and HCO+ (1-0) maps of a portion of the H_2 emission ridge. (The velocity range is -20 to -10 km/s for each map, and the offsets are from a (0,0) point of $6^h\ 14^m\ 43^s$, 22 23' 00" (1950).) The resolution for these maps is higher than the H_2 map, and the emission is clearly highly structured. The emission ridges for the two maps are coincident with the H_2 emission ridge. The location of most of the CO and HCO+ emission peaks are identical; however two of the peaks are located a beamwidth apart. Since the lines were observed simultaneously this offset is probably real; however observations of higher excitation lines are required to determine whether this is due to differences in

excitation conditions or chemical abundances between the peaks.

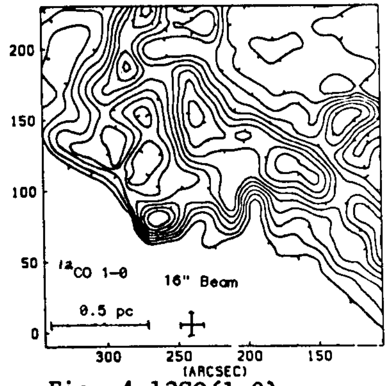

Fig. 4 12CO(1-0)

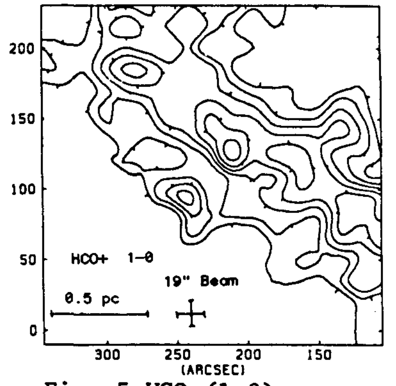

Fig. 5 HCO+(1-0)

The high velocity resolution attainable for these lines allows a detailed investigation of the shock structure within the source. Figures 6 & 7 present profiles of the CO and HCO+ lines, taken with 0.6 km/s resolution, at the brightest H_2 emission peaks (the top profile is from the bright peak at the NW end of the ridge, and subsequent profiles are from positions moving along the H_2 ridge towards its NE end; the profiles in lines 7 & 8 are from the region of the H_2 emission peak). The profiles are complex, and vary considerably from location to location. At each position, however, the CO and HCO+ profiles are very similar (apart from the rest-velocity spike). Particularly noteworthy are the differences between the two brightest H_2 peaks even though they have comparable H_2 fluxes (compare profiles in lines 1 & 2 with 7 & 8). For profile 5 there is no rest velocity component, the emission starting at -40 km/s and extending to -90 km/s with the HCO+ intensity exceeding the CO intensity.

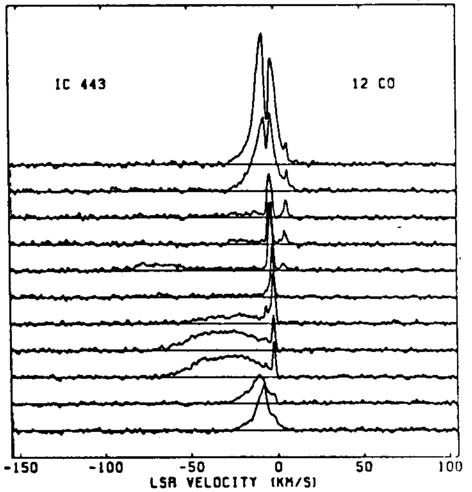

Fig 6. CO profiles at H_2 peaks.

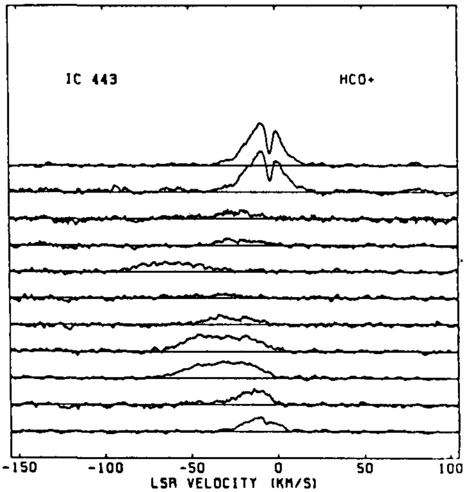

Fig. 7 HCO+ profiles at H_2 peaks.

Discussion: The data have presented clear evidence for the presence of a shock, driven by the expanding gas of a supernova remnant, within a molecular cloud. In this section three aspects of the molecular

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shock in IC 443 are briefly described; further details can be found in Burton et al. (1987). They are the origin of the shocked gas, the cooling of the hot molecular gas and a model for the source.

The similar morphology of the shocked H_2 and high-velocity HI are suggestive of a partially dissociative shock. The shock leaves behind it accelerated molecular and atomic gas, but little ionised gas. The degree of dissociation varies from point to point, and can be determined from a comparison of the column densities of shocked CO and high-velocity HI. Another possibility is that along each line of sight are contained regions of dissociated atomic gas and regions of shocked molecular gas, the molecular gas presumably remaining in dense clumps where the shock velocity is lowest. A comparison of the emission velocities with those of the fine structure lines of OI and SiII, whose emission is more sensitive to higher velocity shocks, may help discriminate between the models.

Nearly all the emission from IC 443 at optical and near-IR wavelengths is line emission. The H_2 data can be used to investigate the relative importance of H_2 line cooling in the shocked molecular gas. For the H_2 emission peak, estimating the mechanical luminosity delivered per unit area to the shock front (from the X-ray pressure driving the expansion) and equating this to the energy radiated away through H_2 lines, suggests that approximately 80% of the energy input to this region is in fact radiated away through H_2 lines. Since the degree of dissociation appears to be large, a significant fraction of the mechanical energy must also go into dissociating the molecules. We suggest, therefore, that molecular hydrogen line radiation and dissociation provide major, if not the dominant, coolants for the gas.

The ring-like appearance of the H_2 emission ridge, situated between the optical emission lobes, suggests a model for the source. We assume that the quiescent molecular cloud running NW-SE across the source, and roughly bisecting the optical shell, actually contains the SNR. A possible history for IC 443 is that the SN exploded within the remnant of a molecular disk left over from the formation of the star which exploded. The expanding shock wave is running into this disk, compressing and heating the gas, and forming a shell on its inside surface. The shocked molecular and atomic lines are emitted from this shell, and are observed as a thin ring. Above and below the disk the expansion is less impeded, and the blast wave has broken out of the molecular disk and is shocking lower density neutral gas, producing the $H\alpha$ emission of the optical lobes.

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