The Azimuthal and Radial Distributions of HI and H_2 in NGC 6946

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Abstract. We have completed a study of the atomic and molecular components of the ISM in NGC 6946. The distribution of molecular clouds has been determined from a fully sampled CO map of the inner disk (R < 8 kpc) using the 14-meter telescope of the FCRAO (HPBW = 45"). The distribution of atomic gas was derived from VLA observations at 40" resolution in the D configuration. When comparing the global CO and HI properties with other components of the galaxy, we find that the azimuthally averaged radial distributions of CO, Hα, radio continuum and blue light all exhibit similar roughly exponential falloffs, while the azimuthally averaged HI surface densities vary by only a factor of 2 out to R = 16 kpc. This indicates that while the Hα/CO ratio is approximately constant with radius, the CO/HI ratio decreases by a factor of 30 from the center of the galaxy to R = 10 kpc.

INTRODUCTION

To better understand the cycling of the interstellar medium and the star formation efficiency in galaxies, we have undertaken a multi-wavelength study of the ISM of the face-on Scd galaxy, NGC 6946. This galaxy has been well-studied by a number of authors. Photometric data from Ables (1971) and Elmegreen and Elmegreen (1984) indicate the exponential nature of the blue and I band luminosity profiles. Hα studies by DeGioia-Eastwood et al. (1984) have been used to infer the massive star formation rate. The HI distribution has been determined at a resolution of 2' by Rogstad, Shostak and Rots (1973). Radio continuum emission has been observed at many wavelengths (cf. Klein et al. 1982; van der Kruit et al. 1977). Observations of the CO distribution have previously been determined (Morris and Lo 1978; Rickard and Palmer 1981; Young and Scoville 1982), and most recently, an interferometric study of CO in the central 1' of this galaxy (Ball et al. 1985) has uncovered a molecular bar ~45" long. In this paper we present the results of a complete ^{12}CO and HI study at moderate resolution.

DATA AND RESULTS

We have made ^{12}CO observations at more than 100 positions in NGC 6946 with the 14-meter antenna of the Five College Radio Astronomy Observatory, and have fully sampled the inner 6' of this galaxy. Figure 1 shows a sample of the CO spectra attained at radii < 2.'25, all plotted on the same scale. The CO intensities peak in the center of the galaxy, and then fall off fairly smoothly with radius, although azimuthal variations of factors of 3 are observed. We observe 2 smaller CO peaks to the northeast and northwest of the galaxy in the

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Star Formation in Galaxies

direction of two major optical spiral arms. Using the standard conversion of CO intensities to H_2 surface densities (Young and Scoville 1982) we find the H_2 density in the central 45" to be 3.3×10^{22} atoms cm^{-2} with the lowest observed values of $<6\times10^{20}$ atoms cm^{-2} in the disk of this galaxy.

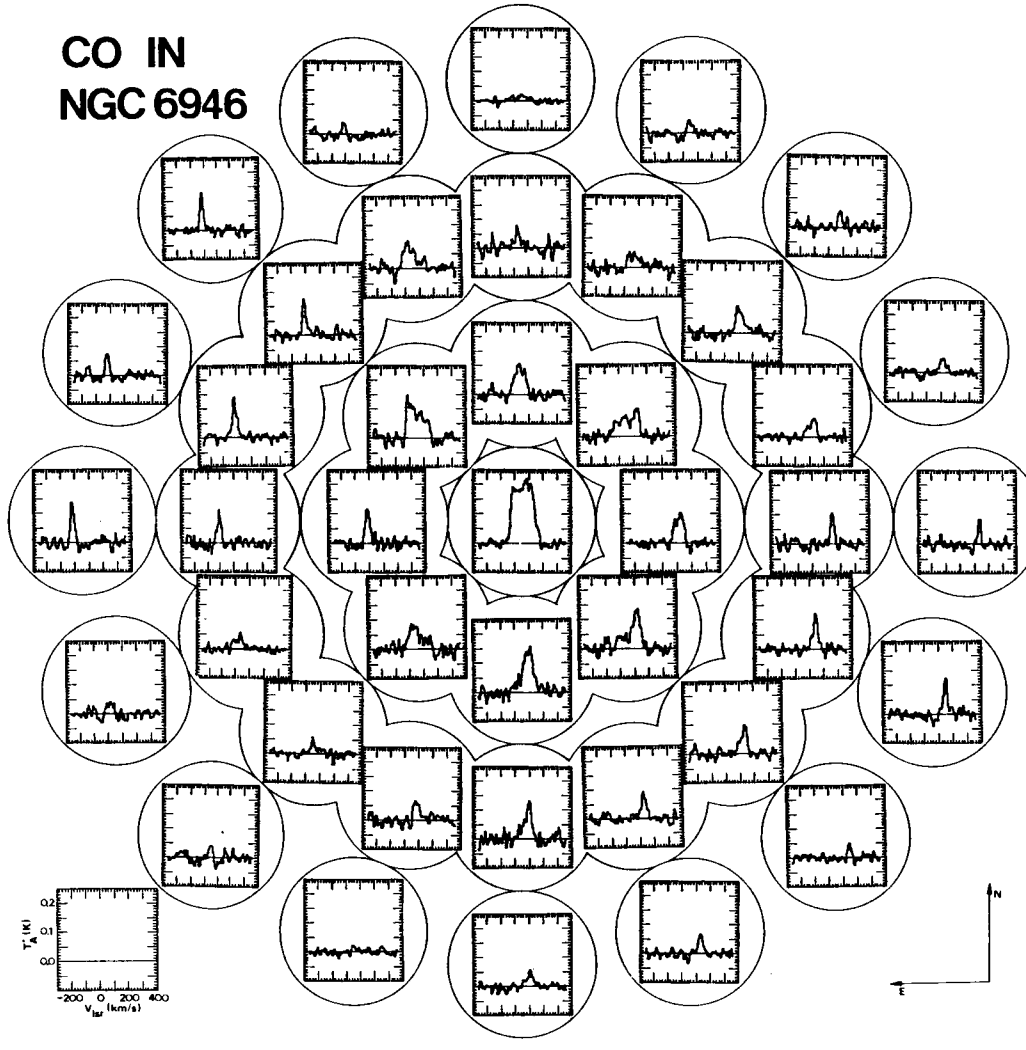

Figure 1. A sample of the CO spectra attained at radii <2'.25 all plotted on the same scale. The circles indicate the positions where the observations were made. These data represent ~1/2 of the complete CO map of NGC 6946. The box in the lower left hand corner indicates the scale of all the spectra.

The 21-cm line data were obtained with the VLA in the D configuration, where the resolution of the synthesized beam was 40"×37". We observe HI emission at greater than the 3σ level out to a radius of 30 kpc, with HI spiral structure apparent in the outer disk, well beyond where the optical arms are seen (see Figure 2). The central surface density of HI is 2.5×10^{20} H cm^{-2} with extreme values over the entire HI disk of 2.1×10^{20} to 2×10^{21} H cm^{-2}. There are two noticeable HI peaks located ~4' to the northwest and northeast of the center which are ~2'.5 × 2'.5. The peak to the northeast contains about 2.4×10^{8} M_0 of HI in an area of 19 kpc^2, and is roughly coincident with the largest, high surface brightness spiral arm in the optical disk. The stronger peak to the northwest of the center contains about 3.8×10^{8} M_0 of neutral gas in a region of 28 kpc^2, and is also coincident with an optical spiral arm. The HI surface densities in these regions are ~14 M_0 pc^{-2}. We also observe several resolvable

HI depressions larger than 45" (2.2 kpc) across in this galaxy to the north and southwest of the center, as well as in the central region itself.

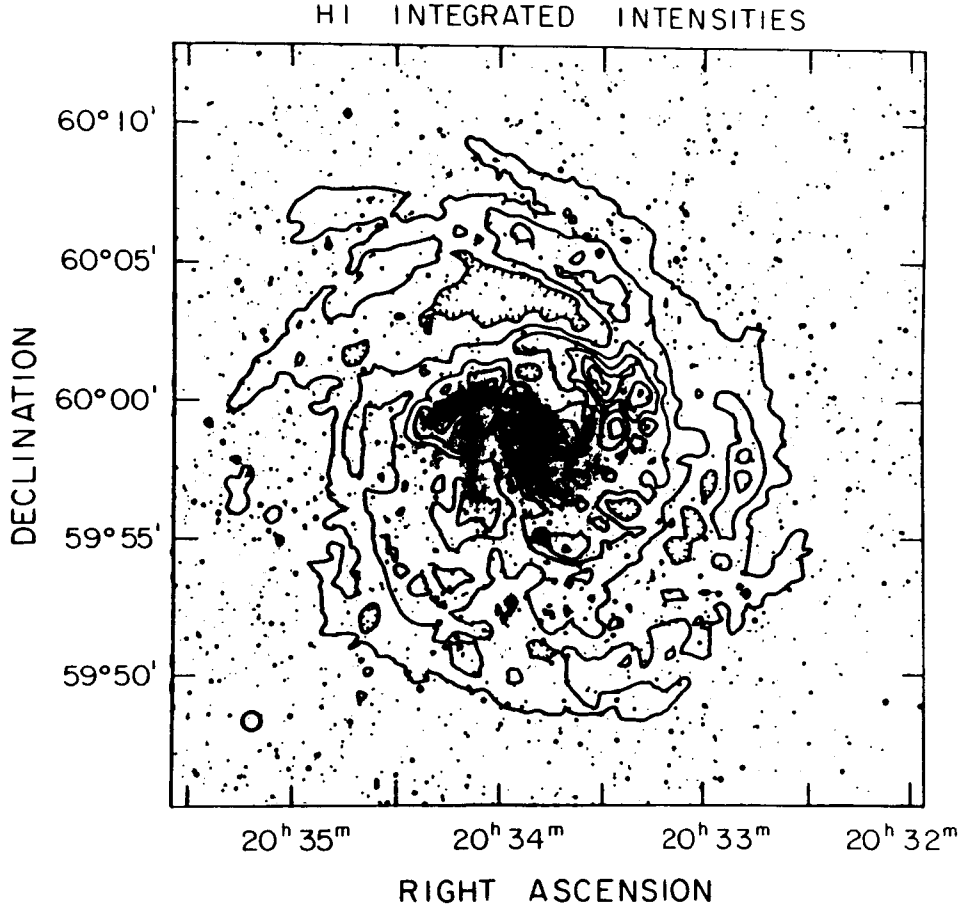

Figure 2. A contour representation of the total HI integrated flux distribution superposed on an enlargement of the Palomar Sky Survey print. The contour levels range from 0.2 to 3.0 Jy km s^{-1} and are separated by 0.4 Jy km s^{-1} intervals. Regions of HI depletion are represented by tic marks on the contours. The HI synthesized beam is shown in the bottom left hand corner of the figure.

COMPARISONS OF HI AND H_2

In Figure 3 we show the H_2/HI ratio as a function of the molecular and atomic surface densities for 89 positions at R < 3' in the galaxy. We have made linear fits to the data for each of the plots, and find that the H_2/HI ratio is correlated with H_2 surface density and anti-correlated with HI surface density. These plots indicate that an increase in the H_2/HI ratio is due to an increase in the H_2 density as well as a slight decrease in the HI density in the inner disk of NGC 6946. Thus, fluctuations in the ISM of this galaxy are dominated by the molecular component rather than the atomic gas.

We have computed the azimuthally averaged radial distributions of HI and H_2 in NGC 6946, and have compared them with the blue luminosity (Ables 1971), Hα (DeGioia-Eastwood et al. 1984), I band (Elmegreen and Elmegreen 1984) and radio continuum (van der Kruit et al. 1977) profiles in Figure 4. The radial distributions of CO, Hα, radio continuum, blue and I band all exhibit similar roughly exponential falloffs (scale lengths = 4-6 kpc), while the azimuthally averaged HI surface densities vary by only a factor of 2 out to R = 16 kpc.

Thus the atomic gas distribution is the only component of NGC 6946 whose shape differs from the rest. This indicates that while the Hα/CO ratio is approximately constant with radius, the CO/HI ratio decreases by a factor of 30 from the center of the galaxy to R = 10 kpc.

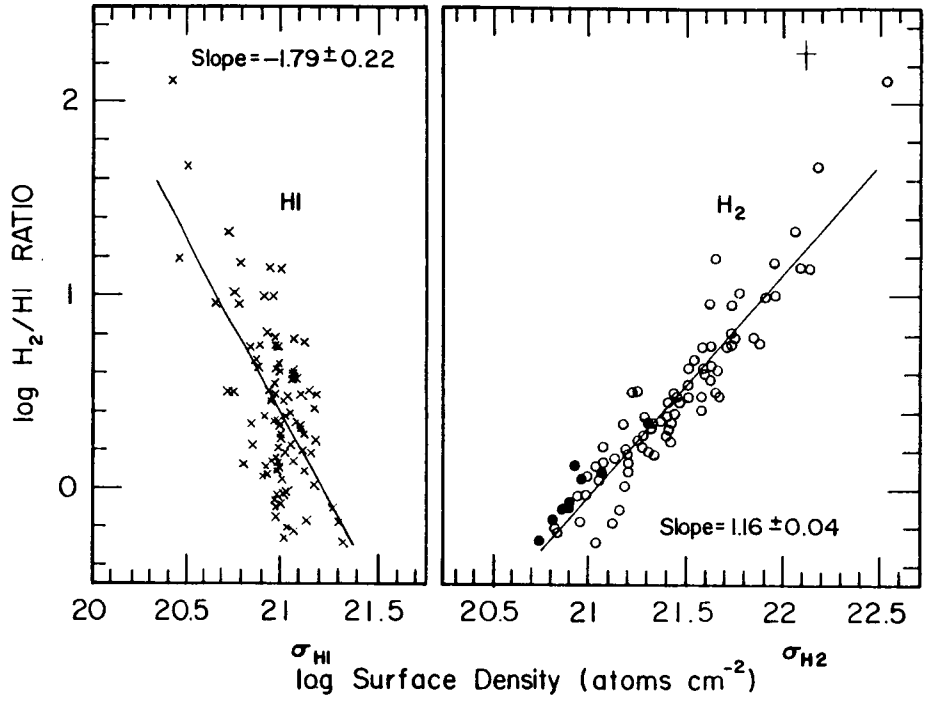

Figure 3. H_2/HI ratio as a function of the (a) atomic and (b) molecular surface densities for 89 positions in the galaxy. A typical error bar is shown in the upper right hand corner of the plot. Filled circles on the H_2 plot represent upper limits to the CO intensity, and thus the H_2 surface density.

We interpret the CO/HI ratio as the efficiency of molecular cloud formation from the atomic medium, and the Hα/CO ratio as the star formation efficiency (SFE) from the molecular medium. Therefore, while the SFE is constant with radius (DeGioia-Eastwood et al. 1984) the cloud formation efficiency decreases sharply with radius. That is, once molecular clouds are formed, stars are produced at a rate which is proportional to the mass of the molecular clouds. The formation of molecular clouds in the outer parts of NGC 6946 may be greatly reduced due to the decreasing volume density of atomic gas. The optical edges of galaxies, therefore, probably reflect the edges of the molecular disks where the formation of molecular clouds from atomic clouds is greatly reduced due to the increasing HI scale height.

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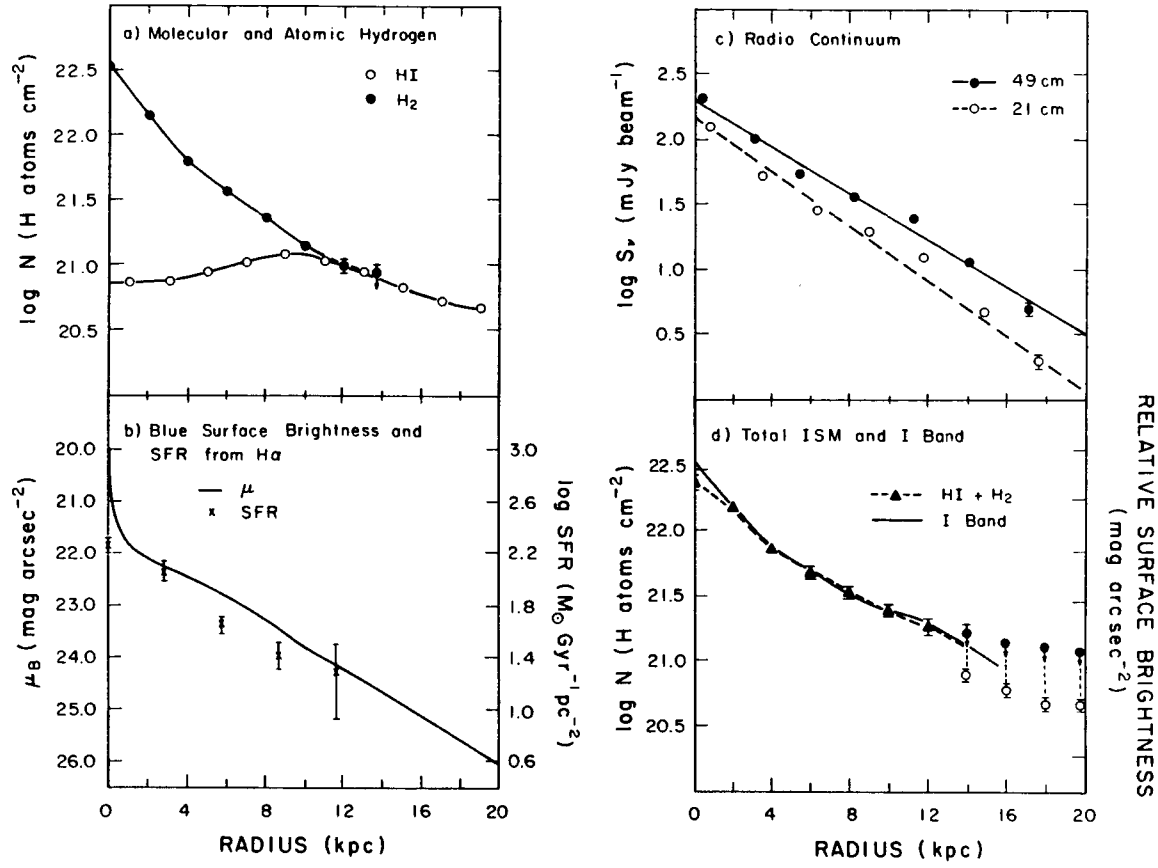

Figure 4. (a) The azimuthally averaged radial distributions of HI and H_2 surface densities. (b) The blue surface brightness radial profile from Ables (1971) and total SFR's calaculated from Hα observations of DeGioia-Eastwood et al. (1984). (c) Radial continuum radial distributions of van der Kruit et al. (1977). (d) I band (Elmegreen and Elmegreen 1984) and total ISM (HI + H_2) radial distributions. At radii greater than 12 kpc, the closed circles in panel d represent HI + H_2 upper limits and the open circles represent the HI lower limits to the total ISM density.

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