S96-90
309676

N91-14196

High Brightness Neutral Hydrogen in M31: A New Probe of Interstellar Pressure ?

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An observational parameter of our own Galaxy, the peak brightness temperature of neutral hydrogen in emission, was determined almost twenty years ago (Burton 1970). This quantity, although possessing a degree of local variations, has a remarkably consistent peak value of 125 K towards spiral arm segments with a few isolated peaks extending to 135 K, once sufficient spatial and velocity resolution are used ($\lesssim$ 70 pc, $\leq$ 5 km/s) to resolve the emission peaks. The higher spatial and velocity resolution of more recent surveys has not led to the detection of higher brightnesses. For many years this remarkable observational result has received little attention, primarily because similar data for other galaxies, which would allow a meaningful comparison and analysis, did not exist. Recently this situation has changed. A Westerbork survey of M33 (Deul and Van der Hulst 1987, and private comm.) with 40 pc x 8 km/s resolution has revealed consistent peak values of only 95 $\pm$ 5 K (although there is still some question of whether the velocity resolution was sufficient in this case), while a VLA survey of M31 (Braun 1989a) with 35 pc x 5 km/s resolution has shown consistent peak values but at a temperature of 155–165 K. It has become clear that although peak HI brightness seems to be a well-defined quantity within individual galaxies (with a degree of local variation) there are very significant differences in this quantity amongst different galaxies.

A complex interplay of processes is thought responsible for determining the kinetic temperature of HI (e.g. Draine, 1978; Kulkarni and Heiles, 1988) with the dominant cooling due to collisional excitation of heavy elements by H atoms and heating due to photoelectric emission from dust grains. Steady-state temperature calculations, as depicted in Figure 7 of Draine (1978), illustrate the stable ISM phases (where the curves have slope < 1) at about 10^4 K and between some 10's and 100's K depending on p/ζ, the ratio of gas pressure to effective primary ionization rate. These calculations show that the steady-state gas temperature depends upon the metallicity, grain depletion, ionization rate and gas pressure. Somewhat counter-intuitively, gas temperatures are expected to be lower for higher pressures and/or lower ionization rates such as might be expected in evolved star-forming complexes where the most luminous stars have already become supernovae, adding pressure but diminishing (after the first $\sim 10^4$ years) the ionizing photon flux. While there appear to be a large number of variables and time-dependant phenomena may also play an important role, all of these quantities are in fact related to each other by the current and previous rates of massive star formation. Such a parameterization may simplify the dependancies illustrated Draine's Figure 7. For the purposes of illustration the three data points noted above can be plotted on the "average depletion" curve in this figure (even though the dust properties of M33 are likely to be rather different than for M31 or the Galaxy). The galactic value corresponds to a value of $\log p/\zeta = 2.82$ in reasonable agreement with the best available estimates of about 2.7 (e.g. Kulkarni and Heiles 1988). The values for M33 and M31 correspond to $\log p/\zeta = 3.26$ and 2.68 respectively. This ranking in $\log p/\zeta$ reflects the relative star formation rates in the three galaxies. Although some improved calculations of dust heating of gas have now been done (e.g. Lepp and Dalgarno, 1988), a complete analysis incorporating the developments of the last ten years is still lacking. The relationship between HI kinetic temperature and observed brightness temperature in emission is also nontrivial in general, since it depends on the distribution of opacity and temperature occuring along the line of sight. However, the observed galactic values of peak HI emission are consistent with the upper envelope of optically thick kinetic temperatures (cf. Payne, Salpeter and Terzian 1983) so that it may be possible to relate these quantities in regions where column densities are sufficiently high.

A number of important points are illustrated in Figure 1 presenting small portions of the extensive database that has been assembled by our team to study M31 (VLA HI: Braun 1989a; VLA 20cm continuum: Braun 1989b; KPNO H_α, [SII], B and R: Walterbos and Braun 1989; INT TAURUS H_α: Brinks, Unger and Braun 1989). A region about 2 kpc on a side with major and minor axis coordinates (X,Y) as indicated is shown in [SII] (6716+6731), H_α, and 20 cm continuum on the left and in integrated HI and peak HI brightness on the right. All images are shown at an identical resolution of 10 arcsec. Optically this field is dominated by the giant (about 300 by 250 pc) HII region complex at X = 40.'8, Y = –6.'8 which is a part of region 775 in the list of Pellet et.al (1978) wi observed luminosities of 1.51 ± 0.07 and 0.49 ± 0.02 × 10^{38} erg s^{-1} in H_α and [SII] respectively. T contour levels and grey-scale of the [SII] image were chosen to be exactly half those used in H_α so th regions which appear similar in the images have the ratio 0.5. Compact HII regions and condensatio can be seen to have a ratio in the range 0.1 to 0.3, while the region of diffuse ionized gas between 4 < X < 44', and –10' < Y < -3' has a very consistent ratio of 0.5 (see also Walterbos and Braun, the proceedings). A newly discovered supernova remnant (SNR) with ratio > 1 can be seen at X = 45 Y = –5.2. The radio continuum image shows discrete counterparts for some of the HII regions ar SNR in the high resolution contours. However, the underlying low resolution (60 arcsec) grey-sca highlights the diffuse (primarily) non-thermal radio emission. The diffuse radio surface brightness this region corresponds to minimum energy magnetic fields of a few μG. This component is very we correlated with the diffuse ionized gas seen in H_α and [SII] with the same suggestion of a diagon edge running from (X,Y) = (42,–10) to (X,Y) = (44,–6). Integrated HI in this region shown at to right shows values in the range 1500 to 5500 K km s^{-1} but relatively little structure that reflects th vigorous star formation activity. The peak HI brightness shown at center right on the other hand ha values between 60 and 140 K and shows a clear anti-correlation with the ionized gas. In particular, th diagonal edge noted above is well-defined and forms one edge of the low-peak-temperature "cavity" i which the entire ionized/synchrotron complex is embedded. The anti-correlation of peak HI brightnes with H_α emission is very general, both on scales of 100's of pc and of kpc's. The highest observed H brightnesses of 140–180 K are concentrated near (X,Y) = (50,2) a gas-rich local minimum in curren star formation activity within the so-called 10 kpc ring.

These tantalizing results have prompted us to embark on an observational program directed at sample of 11 nearby galaxies: NGC 55, 247, 7793, 3031, 2366, 2403, 4236, 4826, 4736, 4244, and 5457 We hope to determine the gas properties and phases as a function of both galaxy type and positio within the galaxies utilizing high resolution HI observations and optical narrow band imagery an spectroscopy which are now underway.

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Fig. 1a–e.—Phases of the ISM in a 2 kpc square region of M31. Coordinates are major and minc axis coordinates (but labeled galactic latitude and longitude), with north-east to the right, in units c arcminutes. **a.** Contours of [SII] surface brightness (smoothed to 10") at (-1, 1, 2, 4, 8, 16, 32 an 64) times 1.66 $\times 10^{-17}$ erg cm^{-2} s^{-1} $arcsec^{-2}$ on a linear grey-scale from 0 to 8.3 $\times 10^{-17}$ erg cm^{-} s^{-1} $arcsec^{-2}$. The sampled region is enclosed in dashed lines. **b.** Contours of H_α surface brightnes (smoothed to 10") at (-1, 1, 2, 4, 8, 16, 32 and 64) times 3.32 $\times 10^{-17}$ erg cm^{-2} s^{-1} $arcsec^{-2}$ on linear grey-scale from 0 to 16.6 $\times 10^{-17}$ erg cm^{-2} s^{-1} $arcsec^{-2}$. The sampled region is enclosed i dashed lines. **c.** Contours of λ 20 cm continuum emission (smoothed to 10") at (-1, 1, 2, 4, 8 and 16 $\times 150\mu$Jy/ 10" beam on a linear grey-scale (smoothed to 60") from 0 to 2 mJy/60" beam. **d.** Contour of integrated HI at 3000 and 4000 K km s^{-1} on a linear grey-scale from 1650 to 3950 K km s^{-1}. **e.** Contours of the peak HI brightness (10" x 5 km/s resolution) at 60—140 K in steps of about 20 K o a linear grey-scale from 50 to 100 K.

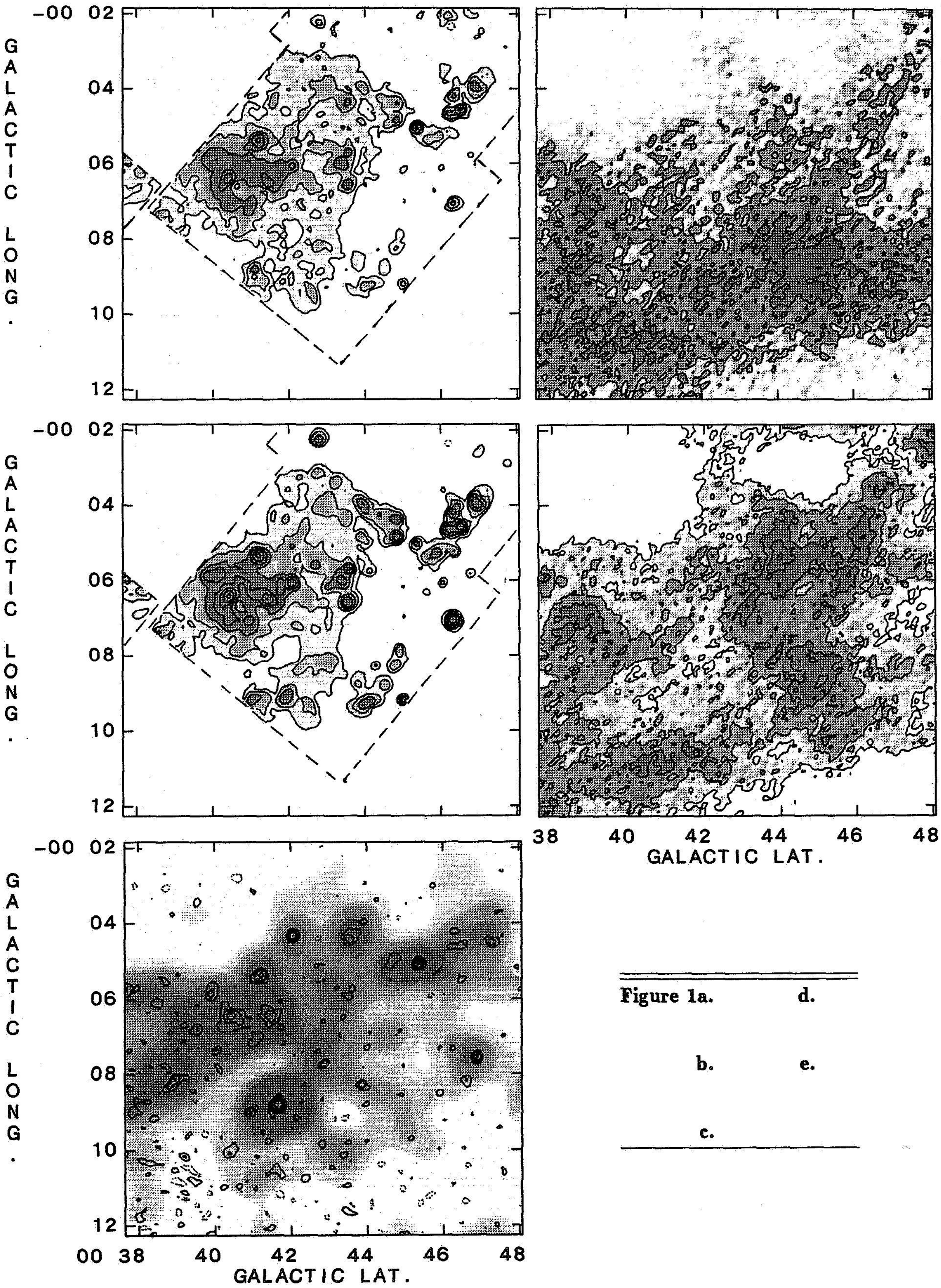

Figure 1a. **d.**

b. **e.**

c.