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A NEW DISTANCE TO CYGNUS X-3

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ABSTRACT

Cygnus X-3 was observed with the Very Large Array[1] at 21 cm wavelength during the outburst of 1982 October. A high-sensitivity spectrum of the galactic absorption was obtained, which shows absorption lines at higher negative velocities than shown by previous spectra. A conservative interpretation of this spectrum gives a lower limit for the distance to Cyg X-3 of 11.6 kpc × (π_0/10 kpc), which is significantly larger than earlier estimates. The absorption spectrum is consistent with Cyg X-3 being extragalactic.

Subject headings: interferometry — radio sources: 21 cm radiation — radio sources: variable — X-rays: sources

I. BACKGROUND

Cygnus X-3 is an extraordinary object. Observationally, it has curious properties at all wavelengths, from centimeter waves to 100 MeV gamma-rays (summarized by Vestrand and Eichler 1982). In the radio, it has had several violent outbursts, in which its flux density at 20 cm increases to about 10 Jy from a quiescent level of about 20 mJy. The most recent outburst came in 1982 October (Geldzahler *et al.* 1983); the first known outburst was in 1972 September (e.g., Hjellming 1973). Such an outburst provides an opportunity to obtain a distance estimate by observing absorption by galactic neutral hydrogen at 21 cm. The presence of absorption lines at various velocities can be translated using a kinematic model of galactic rotation to give a lower limit to the distance; in some cases, the absence of lines at velocities where 21 cm emission is seen nearby can give an upper limit as well, but this is less secure (e.g., Weisberg 1978; van Gorkom *et al.* 1982). This was attempted for Cyg X-3 in 1972 by several groups (e.g., Lauque, Lequeux, and Nguyen-Q-Rieu 1972; Chu and Bieging 1973), but the instruments available at that time had limited sensitivity and were subject to confusion by small angle fluctuations in the H I emission nearby. During the 1982 outburst, Cyg X-3 was observed with the Very Large Array to obtain a sensitive, reliable 21 cm absorption spectrum with high-velocity resolution.

II. OBSERVATIONS

The observations were made on 1982 October 11, using nine antennas from the B array of the VLA (Thompson *et al.* 1980). The bandwidth was 165 km s^{-1} (781 kHz) with a spectrometer channel separation of 1.29 km s^{-1}, centered on $V_{LSR} = -36$ km s^{-1}. Ordinary data taking and calibration procedures were followed. To obtain the final spectrum from the calibrated data, I used the program PASSUM, which vector averages the cross-correlation data, giving the spectrum of the field center (e.g., Dickey 1982). The spectrum is shown in Figure 1, which plots absorption ($e^{-\tau}$) versus velocity on two scales. The upper curve shows the full range of optical depth, while the lower shows the details of the spectral baseline and weak absorption features ($\tau < 0.1$). The rms noise in $e^{-\tau}$ is about 6×10^{-3}. Of particular interest is a weak line with $\tau = 0.028$, i.e., at the level 4.7 σ, and a center velocity of -81.3 km s^{-1}. For the skeptical, the last channel with $\tau > 0.05$ on the edge of the deep absorption is at a velocity of -79 km s^{-1}. The most negative velocity showing absorption is important because it implies a lower limit to the distance. In comparison, Chu and Bieging (1973) could reliably detect only the deeper line centered at -73 km s^{-1}.

III. DISCUSSION

Distance estimates on the basis of galactic absorption spectra are uncertain in several ways. The presence of an absorption line provides a lower limit of some kind, but since spin temperatures vary widely in interstellar H I, the absence of absorption at velocities which show emission does not automatically imply an upper limit. In this case, the Maryland–Green Bank survey shows weak emission to about -110 km s^{-1}, but even so the absorption spectrum is consistent with the source being extragalactic. Even the minimum distance is subject to at least two sources of systematic error. The first is the random velocity distribution of the absorbing clouds themselves, which always causes an overestimate of the distance to the continuum source (Shaver *et al.* 1982).

[1]The Very Large Array is operated by the National Radio Astronomy Observatory under contract with the National Science Foundation.

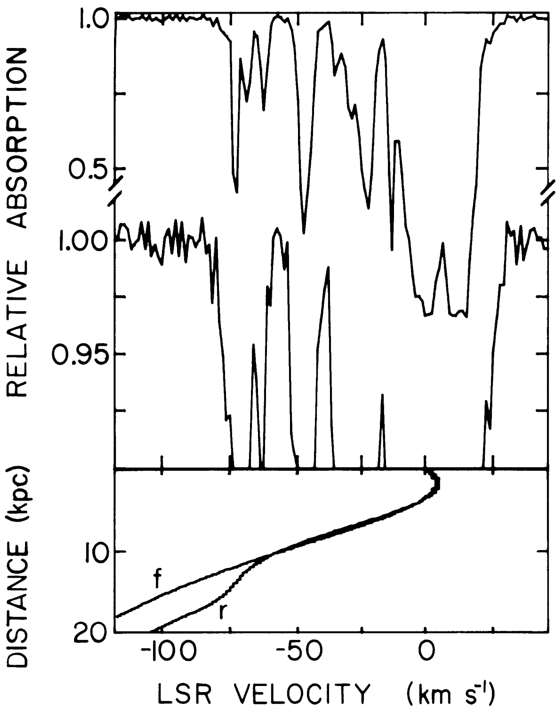

FIG. 1.—The absorption spectrum toward Cyg X-3 observed with the VLA. The upper trace is the full spectrum; the lower trace shows the details of $0.0 < \tau < 0.1$. The two rotation curves discussed in the text are illustrated at the bottom, with distance scaled on the left in kpc. The rising rotation curve corresponds to the r curve; the flat rotation curve corresponds to the f curve.

For clouds with 21 cm optical depths greater than 0.1, this distribution has an rms of 5.3 km s^{-1}; for clouds with $\tau < 0.1$, the rms increases to 11.5 km s^{-1} (Dickey, Salpeter, and Terzian 1978). Adding 1 σ of this random velocity distribution to the velocity of the weak line at -81.3 km s^{-1} gives -69.8 km s^{-1}; adding 1 σ to the highest negative velocity where $\tau = 0.1$ (-74.6 km s^{-1}) gives about the same (-69.3 km s^{-1}). To find a conservative minimum distance, I assume -69.5 km s^{-1} to be the component of radial velocity due to galactic rotation for the most distant absorbing cloud intervening between us and Cyg X-3.

Still more assumptions are needed to interpret this velocity as a distance. The simplest such assumption is that galactic rotation is circular and azimuthally symmetric, i.e., described entirely by some rotation curve; but there is by no means consensus on the form of the rotation curve outside the solar circle. CO data (Blitz 1979) suggest a rising rotation curve. The angular velocity corresponding to this rotation curve is given by (Kulkarni and Blitz 1981)

$$\omega = 130.97 - 20.76\varpi + 1.288\varpi^2 - 0.0271\varpi^3 \quad (10 < \varpi < 18.5),$$

$$\omega = 289.6/\varpi \quad (\varpi > 18.5),$$

where ω is in (km s^{-1} kpc^{-1}) and ϖ is the galactocentric radius in kpc, assuming the IAU standard solar radius, $\varpi_\odot = 10$ kpc. In this model, the radial velocity of -69.5 km s^{-1} corresponds to a distance of 12.8 kpc $\times$ ($\varpi_\odot$/10 kpc). A simpler model which may also be consistent with known galactic structure is a flat rotation curve, i.e.,

$$\omega = 25 \times (\varpi_\odot/\varpi),$$

which gives a distance of 11.63 kpc $\times$ ($\varpi_\odot$/10 kpc). These are fairly conservative lower limits because of the addition of σ_v to the extreme velocity (above); if we had used -80 km s^{-1}, the minimum distance would have come out 12.7 kpc (flat rotation curve) or 16.2 kpc (rising rotation curve).

Although the H I emission spectrum in this direction (Chu and Bieging 1973) shows gas as far as -110 km s^{-1}, the absence of absorption at these velocities is not sufficient evidence to place an upper limit on the distance to Cyg X-3. At velocities more negative than -85 km s^{-1}, there is a total H I column density of only about 10^{20} cm^{-2}. To show detectable absorption, this gas would have to be in a cool cloud with $T_{spin} < 70$ K. However, the broad, smooth shape of this emission tail suggests much higher temperatures. Probably this is warm gas fairly high above the plane, which has very low optical depth. Stray radiation in the emission survey may contribute a significant fraction of this emission. Extragalactic sources at low latitudes surveyed for H I absorption (Dickey *et al.* 1983) seldom show absorption at velocities with similar faint emission wings. So there is no justification for a maximum distance to Cyg X-1 on the basis of the H I absorption spectrum.

IV. SUMMARY

The 1982 October outburst of Cyg X-3 has provided another opportunity to measure the 21 cm absorption spectrum toward this extraordinary source. The gross features of the spectrum are qualitatively similar to those measured in 1972 (Chu and Bieging 1973), but new details at the high negative velocity end permit a revision of the minimum distance to Cyg X-3. Even after accounting for cloud random motions, and using two different rotation curve models, the lower limit distance comes out to be about 12 kpc (11.6–12.8). No maximum distance can be determined.

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