A DEEP SEARCH FOR 21 cm NEUTRAL HYDROGEN EMISSION IN THE TIGHTLY BOUND GLOBULAR CLUSTER NGC 6388

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Received 20 December 1988; revised 3 March 1989

ABSTRACT

A deep search (15.7 hr integration time) for 1420 MHz H I emission from the tightly bound galactic globular cluster NGC 6388 using the 64 m Parkes telescope revealed no emission at the cluster's position and radial velocity. We derive an upper limit of $\mathscr{M}_{\rm H\,I} = 3.8\mathscr{M}_\odot$ and a ratio $\mathscr{M}_{\rm H\,I}/\mathscr{M}_{\rm cluster} = 2.9\times10^{-6}$.

I. INTRODUCTION

A longstanding problem in galactic astronomy is the apparent absence of significant amounts of dust or gas in globular clusters, despite stellar evolution calculations which suggest that about 10^2 to 10^3 $\mathscr{M}_\odot$ of intracluster material should accumulate between passages of a cluster through the galactic plane (e.g., Tayler and Wood 1975; Frank and Gisler 1976). There are more than two dozen searches for such material in the possible forms of atomic or ionized hydrogen gas, molecular gas (CO, OH, H_2O), and warm or cold dust (see review of Roberts 1988). For many cases upper limits much less than the predicted amount have been established for the gas (Roberts 1988) and the dust (Lynch and Rossano 1989). Reported detections of gas or dust in other clusters are generally consistent with these limits. An exception is the case of M56, for which Birkinshaw *et al.* (1983) suggest that a large amount ($2000\mathscr{M}_\odot$) of H I may be associated with the cluster.

Possible explanations of the discrepancy between the observed and predicted amounts of intracluster material include cluster winds which eject the material and interaction of clusters with the halo gas (see Roberts 1988). In either case, a significant amount of gas or dust is most likely to be present in those clusters with the highest escape velocities. As noted by Roberts, better observational limits for such clusters are desired for testing possible removal mechanisms of the intracluster material.

In this paper we report the results of a deep search for H I from NGC 6388. As a metal-poor ([Fe/H] = -0.6), concentration class III globular cluster, it is the most tightly bound globular cluster known (Harris and Canterna 1979; Zinn 1980; Alcaino 1981). With its large mass (1.3×10^6 $\mathscr{M}_\odot$) and highly condensed core (Illingworth and Freeman 1974), this cluster would be expected to have retained a larger fraction of intracluster gas than any other cluster. From an observational standpoint, NGC 6388 is ideally suited for a deep search. It has a high radial velocity ($V_{\rm LSR} = +87$ km/s) and thus is nearly free of galactic contamination. With an optical diameter of 7′, it is unresolved in the Parkes 14.7′ beam, so all of the gas associated with the cluster is expected to be distributed within the beam. The cluster has previously been searched for H I (Bowers *et al.* 1979), but the results presented herein are estimated to be about 7 times more sensitive because of a longer integration time and a lower system temperature.

[a)] This work was supported by The Aerospace Sponsored Research Program and at the Naval Research Laboratory under contract no. N00014-88C-2475.

II. OBSERVATIONS

The observations were made during 3–4 August 1988 with the Parkes 64 m antenna of the Australian Telescope operated by CSIRO. The 1024 channel digital autocorrelator was used in conjunction with a cooled dual-channel front-end receiver. The autocorrelator was configured into four 256 channel quadrants receiving two orthogonal linear polarizations in both 1 and 5 MHz bandwidths. For the 1 MHz bandwidth, the resulting velocity resolution after Hanning smoothing was 1.64 km/s and the effective velocity range was -20 to $+190$ km/s, based on the rest frequency of 1420.4057 MHz. The 5 MHz data were used primarily to verify the baseline shape in the 1 MHz band. The OH maser sources OH 231.8 + 4.2, R Aql, and RR Aql were used to check the tuning of the system.

A total of 15.7 h of observing was obtained in sets of 10 min integrations made alternately between the cluster and the four cardinal reference points (NSEW), which were offset 15′ from the cluster position (epoch 1950) of $17^{\rm h}$ $32^{\rm m}$ $37^{\rm s}.5$, $-44°$ 42′ 14″.3 (Shawl and White 1986). A noise tube was fired every tenth integration to calibrate the data internally. Flux calibrations were made from daily observations of the continuum source Hydra A, whose adopted flux density was 43.5 Jy. The ratio of unpolarized flux density to antenna temperature was 1.6, and the system temperature was about 45 K.

III. RESULTS AND DISCUSSION

Figure 1 shows the residual line profile obtained from the difference between the on-source spectrum and the average of the off-source spectra, with the cluster's velocity indicated. At the cluster position ($l = 345°.4$, $b = -6°.7$), the max-

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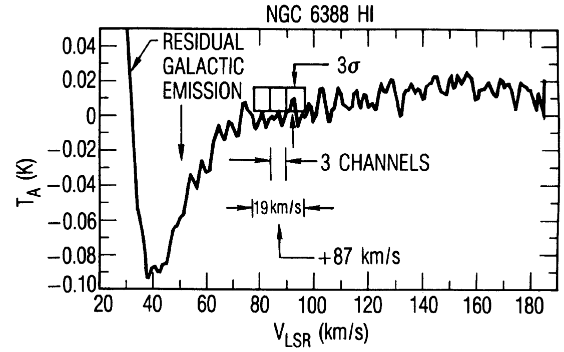

FIG. 1. H I difference spectrum toward NGC 6388. The brightness represents the difference between the signal measured at the cluster's position minus the average signal measured one beamwidth (15′) away at one of four cardinal points (N,S,E,W). The cluster's location is marked at + 87 km/s. The signal at $V_{LSR} < 80$ km/s is due to residual galactic emission. A fifth-order polynomial was fit to the data between $V_{LSR} = 140$ and 200 km/s and the region around + 87 km/s was searched for excusions above the local fit. The bottom of the two boxes, one 3 channels wide and the other 19 km/s wide, lie on the fit and extend 3σ above the mean. No excess emission is evident.

imum velocity in the H I survey of Kerr *et al.* (1986) is about + 45 km/s. Our more sensitive observations indicate probable emission at velocities up to about + 60 km/s. The emission is not completely cancelled by our observing technique, as is to be expected if there are small-scale (15′) spatial variations of the galactic H I. At higher velocities (up to 180 km/s), the residual profile is not flat but indicates a broadband curvature and is offset from 0 K. This may be due to one of three possible effects: sidelobe pickup of high-velocity H I from other directions, high-velocity emission towards but not in the cluster, or instrumental baseline curvature. The fact that the curvature maximizes near 150 and then drops at higher velocities adds some weight to the possibility of an instrumental effect. After application of a fifth-order polynomial baseline correction from 40 to 180 km/s, we find the root-mean-square (1σ) noise level to be 0.005 K (0.008 Jy).

For an unresolved, optically thin distribution, the upper limit to the mass of H I contained in the cluster can be obtained from the equation.

$$\mathscr{M}_{\rm H\,I}(\mathscr{M}_\odot) = 0.236\, D^2\, S\, V_{\rm W}\ ,$$

where D is the distance in kiloparsecs, S is the flux density in Janskys, and $V_{\rm W}$ is the velocity width in km/s of any H I feature (e.g., Roberts 1975). A reasonable detection criterion is that the H I have a flux density at the 3σ level distributed over at least three channels. With $D = 11.6$ kpc (Illingworth 1976), we obtain

$$\mathscr{M}_{\rm H\,I} \leqslant 3.8\, \mathscr{M}_\odot$$

or

$$\mathscr{M}_{\rm H\,I}/\mathscr{M}_{\rm cluster} \leqslant 2.9\times 10^{-6}.$$

If instead we take $V_{\rm W} = 19$ km/s, corresponding to the velocity dispersion of the stars (Illingworth 1976), $\mathscr{M}_{\rm H\,I} \leqslant 14.5\mathscr{M}_\odot$. These upper limits are approximately 7 times lower than those obtained for this cluster by Bowers *et al.* (1979) for the equivalent adopted values of D and $V_{\rm W}$.

Because of its small galactic latitude (− 6°.7) and galactocentric radius (4.5 kpc), NGC 6388 may be an example of a cluster that has recently passed through the galactic plane. Consequently, it alone does not provide a stringent test for models that explain the low gas and dust content of globular clusters. However, observations that establish a comparable fractional ratio of $\mathscr{M}_{\rm gas}/\mathscr{M}_{\rm cluster}$ for clusters with a wide range of galactic latitudes and galactocentric radii may ultimately provide insight into the nature of the mechanism required for the removal of intracluster material.

IV. CONCLUSIONS

A 15.7 hr integration on NGC 6388 at H I λ 21 cm reveals no excess emission above the galactic background. Upper limits to the neutral hydrogen mass have been significantly lowered to $3.8\mathscr{M}_\odot$. If the velocity distribution of the gas matches that of the stars, we obtain an upper limit of $14.5\mathscr{M}_\odot$. These upper limits fall well below predicted masses of intracluster gas based on evolutionary mass-loss scenarios.

This work was supported by The Aerospace Sponsored Research Program and at the Naval Research Laboratory under contract no. N00014-2475. P.F.B. received partial support from the National Science Foundation fund for travel to major foreign telescopes, administered by the National Radio Astronomy Observatory.

REFERENCES

Alcaino, G. (1981). Astron. Astrophys. Suppl. **44**, 33.
Birkenshaw, M., Ho, P. T. P., and Baud, B. (1983). Astron. Astrophys. **125**, 271.
Bowers, P. F., Kerr, F. J., Knapp, G. R., Gallagher, J. S., and Hunter, D. A. (1979). Astrophys. J. **233**, 553.
Frank, J., and Gisler, G. (1976). Mon. Not. R. Astron. Soc. **176**, 533.
Illingworth, G. (1976). Astrophys. J. **204**, 73.
Illingworth, G., and Freeman, K. C. (1974). Astrophys. J. Lett. **188**, L83.
Kerr, F. J., Bowers, P. F., Jackson, P. D., and Kerr, M. (1986). Astron. Astrophys. Suppl. **66**, 373.
Lynch, D. K., and Rossano, G. S. (1989). Astron. J. (submitted).
Roberts, M. (1988). In *The Harlow Shapley Symposium on Globular Cluster Systems in Galaxies*, edited by J. E. Grindlay and A. G. Davis Philip (Kluwer Academic, Norwell, MA), pp. 411–422.
Roberts, M. S. (1975). In *Galaxies and the Universe, Stars and Stellar Systems, Vol. 9*, edited by A. Sandage, M. Sandage, and J. Kristian (University of Chicago, Chicago), pp. 309–357.
Shawl, S. J., and White, R. E. (1986). Astron. J. **91**, 312.
Tayler, R. J., and Wood, P. R. (1975). Mon. Not. R. Astron. Soc. **171**, 467.
Zinn, R. (1980). Astrophys. J. Suppl. **42**, 19.