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LIMITS ON THE INFRARED AND VISUAL LUMINOSITY OF THE INTERGALACTIC H I CLOUD IN LEO

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ABSTRACT

Low surface brightness photometry of the intergalactic neutral hydrogen cloud in Leo sets upper limits on the intensity of this object of 28.0 mag arcsec^{-2} in the V photometric band (μ_V) and 22.8 mag arcsec^{-2} in the K band (μ_K). The corresponding ratio of the H I mass to blue luminosity in the H I emission peaks of the cloud must be greater than 2.9 (solar units) depending on the star formation history of the object. The limits imposed on the star formation rate suggest a strong dependence of this rate on gas density.

Subject headings: galaxies: intergalactic medium — interstellar: matter — stars: formation

I. INTRODUCTION

The intergalactic atomic hydrogen cloud in the Leo Group, discovered by Schneider *et al.* (1983, hereafter SHST), is unique in that it is a cloud of galactic mass which apparently is not a tidal fragment and has no obvious counterpart on the Sky Survey plates. None of the early searches for such clouds produced positive results (Lo and Sargent 1979; Fisher and Tully 1981), implying that clouds of this sort are probably quite rare. Original estimates of the cloud mass, based on virial equilibrium, ranged as high as 10^{11} $M_\odot$. More recent observations (Schneider 1984) suggest that the cloud is orbiting nearby galaxies so that orbital motion could explain the observed velocity dispersion across the cloud. The H I observations have directly shown the existence of at least 1.6×10^9 $M_\odot$ of neutral hydrogen. The actual amount of H I present may be somewhat greater depending on the (unknown) spin temperature (SHST).

Although the H I density is only of order 10^{-3} cm^{-3}, the cloud may have formed stars which could be detected through sensitive surface brightness photometry. This paper presents observational limits for the visual and infrared surface brightness at selected positions in the Leo cloud. Because of the large angular extent and near-uniformity of the H I emission, it was possible to measure very faint emission using small telescopes with large beams. Observations at two wavelengths were made to detect light from either an early-type or a late-type stellar population. These limits constrain both the H I mass to stellar luminosity ratio and the rate of star formation within the H I cloud.

II. OBSERVATIONS

Simultaneous observations in the V (5500 Å) and K (2.2 μm) photometric bands were made using a two-channel photometer. Light from the telescope was split by an ambient temperature dichroic beamsplitter and directed into a photomultiplier and a cryostat with an InSb photovoltaic infrared detector. Both the photomultiplier and the infrared detector had 5.8 mm focal plane apertures which were aligned by moving the photomultiplier in the focal plane. The instrumentation will be described more fully in a forthcoming paper (Skrutskie, Shure, and Beckwith 1985).

Most of the observations were made on the nights of 1983 April 26, and May 4, 12, 13, and 17 with the 60 cm Hartung-Boothroyd reflector near Ithaca, New York. The beam size was 120″, and the response across the beam was uniform to within 10% at both wavelengths. The secondary mirror was chopped at 16 Hz with a throw of 8.′5 to provide background cancellation. Additional observations were made on the nights of June 2, 3, and 4 using the 1.5 m University of Arizona/NASA telescope at Mount Lemmon. The secondary was chopped at 5 Hz with a throw of 8′, and the beam size was 48″.

The analog signals were digitized and synchronously demodulated in a small computer. Differences and squares of differences of the V and K fluxes between the two chopped mirror positions were calculated every chop cycle (i.e., 5 or 16 times per second). Every 20 s, the average fluxes and internal uncertainties were computed. The telescope position was switched between the two chopped image pairs on the sky after these 20 s integrations, and an observation consisted of half the difference in fluxes between the two telescope positions as is standard in infrared photometry (e.g., Low and Rieke 1974).

The statistical uncertainties of the long (several hour) integrations could be determined by examining both the uncertainties of the individual chop cycle fluxes and the statistics of the separate 20 s integrations. Both methods of analysis gave the same result for the V band, and upper limits are quoted as three standard deviations of the mean above zero in each case. For the K band observations, the uncertainties in the 20 s integrations were typically a factor of 1.5 larger than the uncertainties predicted from the individual chop cycles. In this case, the uncertainty used to establish upper limits was the standard deviation of individual 5 minute observations. There was no evidence for drifts or other systematic noise sources among these 5 minute samples.

The flux density scale was calibrated using standard stars. The linearity of the visual photometer at faint light levels was

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checked to an equivalent surface brightness of 23.8 μ_V using faint Space Telescope standard stars, kindly provided by V. Wiśniewski.

The sensitivity of the infrared channel was determined by a combination of amplifier noise and telescope background. The visual night sky background completely determined the noise in that channel through its long term fluctuations. The *V* band night sky brightness at Ithaca and Mount Lemmon was measured to be 20.5 μ_V and 21.2 μ_V, respectively, corresponding to a count rate of $\sim 4000\ s^{-1}$. After 5 minutes of integration time a surface brightness of 26.0 μ_V and 20.8 μ_K could be detected at the 3 σ level. The sensitivity was checked by observing low surface brightness regions in galaxy disks and halos, obtaining positive detections at the level of 26.6 μ_V (8 σ) at about 1.0 Holmberg radii in NGC 4244 in a 90 minute integration, and 21.7 μ_K (5 σ) at about 0.7 Holmberg radii in a 30 minute integration (Skrutskie, Shure, and Beckwith 1985). All measurements were in good agreement with the anticipated exponential falloff of the disk surface brightness with radius.

Figure 1 shows the H I contours of the cloud and the location of the three positions (A, B, and C) observed at *V* and *K*. Positions A and C were chosen to coincide with emission peaks in the H I profiles. Owing to the physical limitations of the telescopes, the comparison beam positions lie on the boundary of the H I emission. If stars exist in the cloud and the H I distribution follows the stellar luminosity, as is the case in normal galaxies and tidal features (Haynes, Giovanelli, and Roberts 1979; Burkhead and Hutter 1981), then any stellar emission in the reference beam positions is likely to be less than 20% of the main beam emission. In addition, the beam and sidelobe structure of the Arecibo circular 21 cm feed may spuriously extend the outer contours of the cloud (Schneider 1984). No foreground stars were visible at any of the beam positions on the Palomar Sky Survey prints. Only upper limits to the *V* and *K* fluxes were obtained at the points observed. Table 1 summarizes these results. Features with a surface brightness of the same order as the limits which do not fill the beam may go undetected, but the limits allow calculations of bounds to the global ratio of mass to luminosity.

III. DISCUSSION

Although the cloud is considerably larger than a typical galaxy of similar total H I mass, the visual and infrared surface brightness is much less than would be seen by spreading the stars of a normal galaxy uniformly over the same area (2 K dashed contour in Fig. 1). For example, the surface brightness of elliptical and face-on spiral galaxies is of order 21 μ_V. Spreading the luminosity out over the area of the cloud results in a surface brightness of about 25 μ_V, easily detectable by our observations. Irregular galaxies typically have a greater mass fraction in H I than spirals and ellipticals. If the Small Magellanic Cloud were scaled to have the same H I mass as the observed H I mass of the Leo cloud and was spread uniformly over the same area, the surface brightness would be 28.4 μ_V, marginally detectable by these observations. On the other hand, if the luminosity is distributed in proportion to the cloud's H I emission, the surface brightness in the density peaks would be 26.4 μ_V. Further, if the actual H I mass of the cloud is greater than the observed lower limit of 1.6×10^9 $M_\odot$, as suspected, the surface brightness would be well above the observed limits.

SHST argue that the cloud is not a tidal plume from one of the nearby cluster galaxies. Our observations support this conclusion. The tidal plume adjacent to NGC 3628 (Rots 1978) in the Leo Triplet resembles the cloud in terms of its H I mass of 5.4×10^8 $M_\odot$, density of 10^{-2} cm^{-3}, and extent of 85 kpc (compared to 1.6×10^9 $M_\odot$, 10^{-3} cm^{-3}, and ~ 100 kpc for the cloud, assuming a distance of 10 Mpc [SHST]).

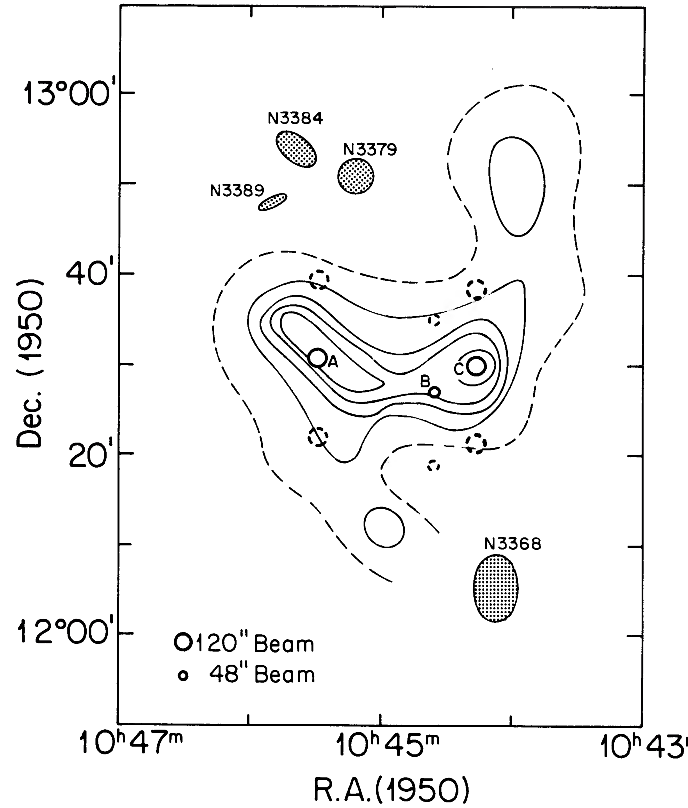

FIG. 1.—Neutral hydrogen map of the intergalactic cloud in the Leo Group. Observed positions are indicated by A, B, and C. Contours are in units of K km s^{-1}. The dashed line represents 2 K km s^{-1}, and the solid line contours are in steps of 10 K km s^{-1}. The reference beam positions are represented by the dashed circles. The HPBW for the H I radio map was 3'.5.

TABLE 1

UPPER LIMITS TO SURFACE BRIGHTNESS[a]

Parameter	Position A	Position B	Position C
V band	27.3	27.5	28.0
K band	22.6	22.2	22.8
Integration time (hr)	1.8	2.0	5.1
Beam size (arc sec)	120	48	120

[a]All limits represent three standard deviations above zero in units of mag $arcsec^{-2}$.

The visual surface brightness in the density peaks of the plume is 25.6 μ_V (Burkhead and Hutter 1981), considerably brighter than the limits for the cloud. Dynamical simulations by Rots indicate that the plume is 8×10^8 yr old. If the fragment formed with a solar neighborhood population, the plume would have to age 25 billion years in order to appear fainter than the visual limit of 28.0 μ_V, assuming tidal disruption ended star formation in the region and that stars do not significantly disperse relative to the H I following this late stage of the tidal encounter. These arguments, in conjunction with those of SHST, suggest that the cloud did not originate as a tidal fragment. The analysis that follows assumes that the cloud is not a tidal fragment and that its age is 10^{10} yr.

a) Stellar Content

The observational limits constrain the ratio of the H I mass to stellar luminosity. The values are derived using fluxes three standard deviations above zero for point C which has the best limits. Assuming a color index of 0.8, typical of spiral galaxies, this visual flux limit implies a blue luminosity of less than $1.8 \times 10^5\ L_\odot\ \mathrm{kpc}^{-2}$. Given a solar neighborhood initial mass function (Miller and Scalo 1979), the corresponding mass in stars can be determined. Assuming a continuous rate of star formation up to the present day, the mean absolute visual magnitude per solar mass in the form of stars is 5.6 with a peak luminosity in spectral class F5. The visual flux limit together with the initial mass function requires less than $4.2 \times 10^5\ M_\odot\ \mathrm{kpc}^{-2}$ in the form of stars including the end products of evolved massive stars.

The H I mass surface density at position C is $5.2 \times 10^5\ \alpha^{-1}\ M_\odot\ \mathrm{kpc}^{-2}$, where α, the ratio of the observed to actual H I mass, is determined from the H I spin temperature and α^{-1} probably lies in the range 2–20 (SHST). The limits require $M_{\rm H\,I}/L_B > 2.9\ \alpha^{-1}$ within one beam. In normal galaxies, $M_{\rm H\,I}/L_B$ is rarely greater than 1.0 (Bothun 1982). Even if $\alpha = 1$, the mass-to-light ratio observed in the cloud is larger than most, if not all, normal galaxies. Since it is likely that $\alpha^{-1} > 1$, the cloud is unique in its low stellar luminosity with respect to its large H I mass. It should be kept in mind that the results presented here represent a surface measurement of $M_{\rm H\,I}/L_B$ with a 2′ beam. H I mass-to-light ratios for galaxies typically use the total H I mass and integrated blue luminosity.

Romanishin *et al.* (1982) have made a study of abnormally low surface brightness spiral galaxies and have found $\langle M_{\rm H\,I}/L_B \rangle = 0.86$, implying that their H I content is nearly twice that of typical late-type spiral galaxies. The intergalactic H I cloud may be an extreme example of these low surface brightness objects. Haynes and Giovanelli (1984) point out that the dependence of $M_{\rm H\,I}/L_B$ on surface brightness in late-type spirals reduces to a dependence of $M_{\rm H\,I}$ on the optical linear diameter squared, that is, H I surface density is roughly constant. Low surface brightness spirals represent an extreme in $M_{\rm H\,I}/L_B$ but fall well within the bounds for normal spirals in the $M_{\rm H\,I}/D^2$ relation. The Leo cloud, with a diameter of 100 kpc and $\alpha = 1$, falls well below these bounds. Either α^{-1} is of order 30, or, as is more likely, it is improper to consider the cloud as an extreme example of low surface brightness spiral galaxies.

There is no guarantee that star formation in the cloud proceeded via a solar neighborhood IMF. If the majority of stars formed were M8 dwarfs ($M_v = 16$, $V - K = 7$, $M = 0.1\ M_\odot$, $L = 8 \times 10^{-4}\ L_\odot$), the infrared limit would allow up to $1.2 \times 10^9\ M_\odot\ \mathrm{kpc}^{-2}$ of these stars. This mass integrated over the entire cloud is more than an order of magnitude greater than the observed H I mass of the cloud. This limit may prove to be interesting if the cloud has a large mass requiring substantial quantities of underluminous matter, as suggested by an application of the virial theorem (SHST).

b) Density Dependence of the Star Formation Rate

It has been argued that the global rate of galactic star formation is a function of the mean galactic gas density traced by H I (Schmidt 1959; Salpeter 1959). If so, the low H I density of the cloud ($\sim 10^{-3}\ \mathrm{cm}^{-3}$) provides an interesting test for this hypothesis in an environment not found in normal galaxies.

The observations constrain the average star formation rate in the cloud to less than $1.1 \times 10^{-15}\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{pc}^{-3}$, assuming a depth along the line of sight of 40 kpc, a solar neighborhood IMF, and a uniform rate of star formation for $\sim 10^{10}$ yr. The peak H I density of the cloud is about $10^{-3}\ \alpha^{-1}\ \mathrm{cm}^{-3}$. In the Galaxy, with an average H I density of $\sim 1\ \mathrm{cm}^{-3}$, the star formation rate is $\sim 7 \times 10^{-12}\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{pc}^{-3}$ (assuming a net galactic rate of 1 $M_\odot$ per year, a diameter of 30 kpc, and a scale height of 100 pc). Unless the cloud is highly flattened so that the line-of-sight depth has been seriously overestimated, these rates imply a strong dependence of the star formation rate upon mean gas density.

It has been suggested that the star formation rate is related to the mean gas density ρ by a power law (rate = $K\rho^n$). Using this relation to quantify the above results (assuming the same proportionality constant, K, for both the cloud and Galaxy), a comparison of the above limits to the star formation rates for the cloud and the Galaxy imply

$$n > \frac{3.8}{3.0 + \log \alpha}.$$

The lower bounds on n are 1.3 and 2.2 for α^{-1} of 1.0 and 20, respectively.

These limits for n agree with bright star and H II region measurements in the Galaxy (Black and Kellermann 1974; Guibert *et al.* 1978). However, Miller and Scalo (1979) point out that n must be less than 0.5 in order to maintain the continuity of the initial mass function derived from the present-day luminosity function. Madore (1977) has shown that when the depletion and dispersal of gas due to star formation is accounted for, as well as spatial averaging over regions of varying density, the observed values of n in the range 1–2 are consistent with an exponent of order 0–0.5 in effect at the time of formation. The measurements presented here are averages over large areas of the cloud. The requirement $n > 1.3$ is then consistent with Miller and Scalo's constraint.

Although this result is consistent with previous work, it does not guarantee a causal correlation between H I density and the star formation rate. It has been suggested that the star formation rate depends strongly on the molecular hydrogen density rather than the H I density (Sanders, Solomon, and Scoville 1984) and that there is no simple relation for the H I/H_2 ratio. In this case any attempt to correlate star formation with H I density would be inappropriate.

IV. CONCLUSIONS

Upper limits to the surface brightness of 28.0 μ_V and 22.8 μ_K were obtained for the most sensitive of three points observed in the neutral hydrogen density peaks of Schneider's cloud. The $M_{\rm H\,I}/L_B$ ratio is at least 2.9 and may be somewhat larger, depending on the unknown spin temperature. This value of $M_{\rm H\,I}/L_B$ is larger than that typically found integrated over entire normal galaxies.

The cloud's low H I density provides a new test for the sensitivity of the star formation rate to the mean galactic gas density in a previously unobserved H I density regime. If the star formation rate depends on some power, n, of the density ρ (ρ^n), then n is greater than about 1.3, in agreement with local observations of star-forming regions.

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REFERENCES

Black, D. C., and Kellerman, S. A. 1974, *Ap. Space Sci.*, **23**, 107.
Bothun, G. D. 1982, in The Comparative H I Content of Normal Galaxies, p. 1 (Green Bank Workshop, April 5–8).
Burkhead, M. S., and Hutter, D. J. 1981, *A.J.*, **86**, 523.
Fisher, J. R., and Tully, R. B. 1981, *Ap. J. (Letters)*, **243**, L23.
Guibert, J., Lequeux, J., and Viallefond, F. 1978, *Astr. Ap.*, **68**, 1.
Haynes, M. P., and Giovanelli, R. 1984, *A.J.*, in press.
Haynes, M. P., Giovanelli, R., and Roberts, M. S. 1979, *Ap. J.*, **229**, 83.
Lo, K. Y., and Sargent, W. L. W. 1979, *Ap. J.*, **227**, 756.
Low, F. J., and Rieke, G. H. 1974, in *Methods of Experimental Physics*, Vol. **12**, ed. N. Carleton (New York: Academic), p. 415.
Madore, B. F. 1977, *M.N.R.A.S.*, **178**, 1.
Miller, G. E., and Scalo, J. M. 1979, *Ap. J. Suppl.*, **41**, 513.
Romanishin, W., Krumm, N., Salpeter, E., Knapp, G., Strom, K. M., and Strom, S. E. 1982, *Ap. J.*, **263**, 94.
Rots, A. H. 1978, *A.J.*, **83**, 219.
Salpeter, E. E. 1959, *Ap. J.*, **129**, 608.
Sanders, D. B., Solomon, P. M., and Scoville, N. Z. 1984, *Ap. J.*, **276**, 182.
Schmidt, M. 1959, *Ap. J.*, **129**, 243.
Schneider, S. E. 1984, personal communication.
Schneider, S. E., Helou, G., Salpeter, E. E., and Terzian, Y. 1983, *Ap. J. (Letters)*, **273**, L1 (SHST).
Skrutskie, M. F., Shure, M. A., and Beckwith, S. 1985, in preparation.

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