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IS THERE MOLECULAR GAS IN THE H I CLOUD BETWEEN NGC 4472 AND UGC 7636?

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ABSTRACT

We present CO observations of the H I cloud located between the Virgo elliptical galaxy NGC 4472 and its dwarf irregular companion galaxy UGC 7636. *ROSAT* observations of the X-ray halo of NGC 4472 show a hole in the X-ray emission at the position of the H I cloud (Irwin & Sarazin 1996). If the hole is assumed to be the result of soft X-ray absorption by some absorbing material within the cloud, the total implied mass of the absorbing material is much larger than the measured H I mass of the cloud. This implies that a large fraction of the cloud is composed of molecular hydrogen. However, the CO observations fail to find the required amount of molecular gas if a Galactic CO-to-H_2 conversion factor is assumed. While a low density in the molecular gas might increase the CO-to-H_2 conversion factor enough to make the CO upper limit consistent with the X-ray absorption prediction, too low a density would allow the H_2 to be dissociated by UV radiation. We conclude that it is unlikely that the required absorbing mass is present. In any case, these observations provide a strict upper limit on the CO content of the H I cloud. © *1997 American Astronomical Society.* [S0004-6256(97)02705-2]

1. INTRODUCTION

The bright Virgo elliptical galaxy NGC 4472 (M49) is believed to be interacting with the dwarf irregular galaxy UGC 7636 (Patterson & Thuan 1992, hereafter PT92; McNamara *et al.* 1994, hereafter M94). Located 5.′5 southeast of NGC 4472, UGC 7636 possesses an optical tail and countertail which are most likely the result of a tidal interaction with the giant elliptical galaxy (PT92). In addition, a cloud of H I gas was found to lie 3.′1 southeast of NGC 4472 (Sancisi, *et al.* 1987), and was most likely removed from UGC 7636 by ram pressure stripping from the hot gas in the X-ray halo of NGC 4472 or by tidal interaction. Three pieces of observational evidence support this claim. First, UGC 7636 is deficient in H I (Sancisi *et al.* 1987), most unusual for a dwarf irregular galaxy. Furthermore, the H I cloud contains roughly the amount of neutral hydrogen expected to be found in a dwarf irregular galaxy with UGC 7636's blue luminosity (PT92). Second, the radial velocity of the cloud (470 ± 5 km s^{-1}; PT92) lies between that of UGC 7636 (276 ± 78 km s^{-1}; Huchra 1996) and NGC 4472 (997 km s^{-1}; Faber *et al.* 1989), which is what is expected if the cloud has been decelerated somewhat by ram pressure from the gaseous X-ray halo after being stripped from the dwarf galaxy. Third, M94 have shown that the shape of the H I cloud and the optical isophotes of UGC 7636 are very similar, suggesting that the stars and H I were gravitationally distorted as one unit, prior to the removal of H I via ram pressure stripping. M94 point out, though, that the similarity in shape might be a coincidence, since it is difficult to explain how gas with a sound speed of only a few km s^{-1} could retain its shape despite differential ram pressure effects as it was decelerated by ~ 200 km s^{-1}.

Recent *ROSAT* X-ray observations of the NGC 4472/UGC 7636 system reveal a hole in the X-ray emission from NGC 4472 at the position of the H I cloud (Irwin & Sarazin 1996, hereafter IS96). This hole is more pronounced at soft X-ray energies than at hard X-ray energies, suggesting that the hole is due to soft X-ray absorption from absorbing material within the cloud. However, the amount of absorbing material needed to produce the hole is far more than the amount of H I measured by PT92 and M94. IS96 find that the required absorbing column density is at least five times the H I value and propose that a majority of the absorbing material is molecular.

In this paper, we present 2.6 mm CO $J=1-0$ observations of the H I cloud. These observations were performed in order to search for the molecular gas believed to be producing the soft X-ray absorption, and to place limits on the molecular content of the H I cloud. A review of the properties of the X-ray hole and the H I cloud is presented in Sec. 2, and our CO observations are described in Sec. 3. The implications of the CO and X-ray observations are discussed in Sec. 4, and our conclusions are stated in Sec. 5. We assume that NGC 4472 and the H I cloud are at a distance of $d=25.8$ Mpc (Faber *et al.* 1989, and a Hubble constant of $H_0=50$ km s^{-1} Mpc^{-1}). However, we give the explicit distance dependence for all observational quantities. At this distance, 1′ corresponds to 7.5 (d/25.8 Mpc) kpc.

2. X-RAY HOLE AND H I CLOUD PROPERTIES

Long *ROSAT* HRI and PSPC X-ray observations of NGC 4472, discussed in detail in IS96, detected a decrease in X-ray surface brightness at the position of the H I cloud. The decrease in surface brightness relative to the region surrounding the hole is 82% (significant at the 3.6σ level) in the HRI image and 28% (significant at the 5.1σ level) in the hard band (0.52–2.02 keV) PSPC image. This suggests that the feature could be due to soft X-ray absorption, as opposed to a decrease in emission at the position of the hole (which would probably have the effect of decreasing the X-ray surface brightness at all energies similarly).

After assuming a thermal model representative of the region surrounding the hole, IS96 calculated the required column density (above that due to the Galaxy) of the absorbing material which would produce such a hole in the X-ray emission, along with the corresponding mass of the absorbing material. Both the HRI and PSPC yielded the same required absorbing mass of about 2.5×10^9 (d/25.8 Mpc)^2 $M_\odot$, with a 1σ lower limit of 1.7×10^9 (d/25.8 Mpc)^2 $M_\odot$. This is to be compared to the H I mass values of $3.1\pm0.5\times10^8$ (d/25.8 Mpc)^2 $M_\odot$ found by PT92 with the NRAO 140 foot telescope in Green Bank, and $1.1\pm0.1\times10^8$ (d/25.8 Mpc)^2 $M_\odot$ found by M94 with the VLA. The Green Bank total mass estimate is probably a more accurate value, since the VLA observations might have resolved out extended H I emission. If the hole in the X-ray emission is real and due to absorption, this implies that H I comprises only about 10% of the absorbing material. Molecular gas seems to be a likely alternative for the remainder of the absorbing material.

It is perhaps worth noting that at the absorbing column densities of interest here, much of the X-ray absorption is due to the oxygen K-edge. Thus, the X-ray observations actually determine the column density or mass of oxygen, rather than of hydrogen. X-ray absorption is nearly independent of the physical state of the oxygen, as long as it is not strongly ionized. The column densities of hydrogen and the masses above were derived assuming solar abundances of oxygen and other heavy elements. If the abundances are lower than solar, as might be expected for gas stripped from a dwarf irregular galaxy (e.g., Garnett *et al.* 1995), then the required hydrogen column densities and masses would be increased.

TABLE 1. Observational parameters.

Date	1996 April 15–17
Telescope	NRAO 12 m
RA(J2000)	$12^h29^m55^s.5$
DEC(J2000)	7°57′43″
Line	CO $J=1-0$
Frequency	115.2712 GHz
Heliocentric velocity	470 km s^{-1}
Effective integration time	30.0 hr
Effective system temperature	414 K
HPBW	55″

3. CO OBSERVATIONS

Having no permanent electric dipole, the hydrogen molecule is not a strong emitter, so CO $J=1-0$ is usually used as a tracer of H_2 in extragalactic systems, and the amount of H_2 is indirectly inferred after assuming a representative CO-to-H_2 conversion factor. In our case, observations of CO are even more appropriate, because the X-ray absorption is primarily due to oxygen and carbon. In molecular gas, much of the carbon and oxygen is in the form of CO, so this species is likely to be the main contributor to the X-ray absorption.

The mass of molecular gas required to explain the X-ray absorption is

$$M_{H_2}\approx 2.5\times10^9\left[\frac{Z(\mathrm{O})}{Z_\odot(\mathrm{O})}\right]^{-1}\left(\frac{d}{25.8\ \mathrm{Mpc}}\right)^2 M_\odot, \tag{1}$$

where d is the distance and Z(O) and $Z_\odot$(O) are the abundance of oxygen in the absorber and the Sun, respectively. The predicted CO flux is then

$$S_{\mathrm{CO}}^{pred}\approx 230\left[\frac{Z(\mathrm{O})}{Z_\odot(\mathrm{O})}\right]^{-1}\left(\frac{X}{X_o}\right)^{-1}\ \mathrm{Jy\ km\ s^{-1}}\ , \tag{2}$$

where X is the CO-to-H_2 conversion factor, and X_o is the standard Galactic value of 3×10^{20} cm^{-2} (K km s^{-1})$^{-1}$ (Wilson & Scoville 1990).

We observed the H I cloud in CO $J=1-0$ (2.6 mm) with the NRAO[1] 12-meter telescope on 1996 April 15–17. The observational parameters are summarized in Table 1. The pointing position for the CO observations was chosen as a compromise between the peak of the H I emission and the position of the hole in the X-ray emission, but both positions are located well within the 55″ half power beamwidth (HPBW) of the CO observations. Observations were made using a nutating subreflector to switch between the source position and a reference position 4′ away in azimuth at a rate of 1.25 Hz. The data for both polarizations were recorded using a 256×2 MHz filter bank spectrometer, which provided a velocity coverage of approximately 1300 km s^{-1}. The spectrometer setup was verified by observations of Orion, and the telescope pointing was checked every two hours with observations of 3C273. Flux calibration was confirmed by observations of Mars. Assuming that the CO clouds are concentrated near the peak of the H I emission and

[1]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

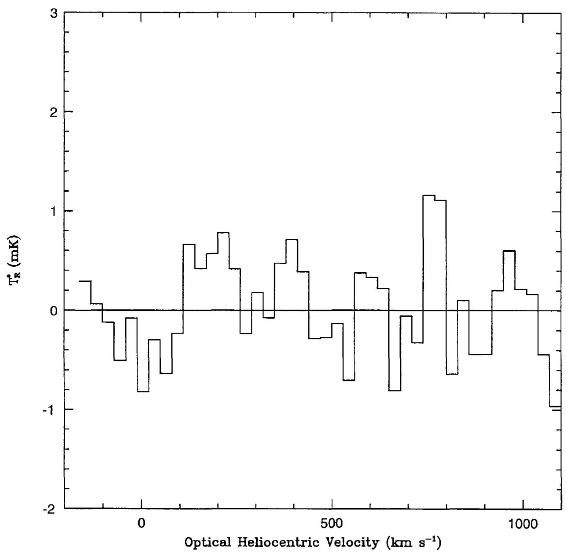

FIG. 1. The CO $J=1-0$ spectrum of the H I cloud ($v=470$ km s^{-1}) between NGC 4472 and UGC 7636. No CO emission was detected, and the 1σ upper limit is $T_R^*<0.7$ mK for the velocity resolution of 30 km s^{-1}.

X-ray hole (for sources smaller than the HPBW), the conversion of the observed T_R^* temperature scale (Kutner & Ulich 1981) into Janskys is approximately 35 Jy/K.

All data were carefully analyzed, and no CO emission was detected. A small number of scans were removed from the data set since they showed signs of baseline instabilities with an rms noise much larger than the theoretical value. The remaining data yielded 30.0 hours of useful integration time (an average of 15 hours for each polarization). The data were smoothed to a resolution of 30 km s^{-1}, and only a zeroth order baseline was removed from the data (Fig. 1). The total integrated CO flux over the velocity range of the H I emission (380–550 km s^{-1}; PT92) is -0.76 ± 1.85 Jy km s^{-1} (1σ). We find a 95% upper limit of the positive CO flux of

$$S_{\rm CO}<3.0 \text{ Jy km s}^{-1}, \tag{3}$$

which is about two orders of magnitude less than the value predicted by the X-ray observations (Eq. (2)).

The most straightforward explanation for the lack of CO emission is that the predicted amounts of CO and H_2 are not present in the H I cloud, and that the X-ray deficit at the position of the hole is not due to soft X-ray absorption. A study of 25 dwarf galaxies by Israel *et al.* (1995) finds that the $M_{\rm H_2}/M_{\rm H\,I}$ mass ratio is less than a few percent in these types of galaxies if a Galactic CO-to-H_2 conversion factor is assumed. Thus, UGC 7636 would be required to have a $M_{\rm H_2}/M_{\rm H\,I}$ ratio two orders of magnitude larger than is observed in typical dwarf galaxies in order to produce the X-ray hole. It is unlikely that an otherwise typical dwarf galaxy could have such an anomalously high $M_{\rm H_2}/M_{\rm H\,I}$ ratio. However, it is not at all obvious that a Galactic CO-to-H_2 conversion factor is appropriate for dwarf galaxies. Israel *et al.* (1995) point out that CO in dwarf galaxies could be underabundant or have very low excitation temperatures, with both effects leading to an increase in the CO-to-H_2 conversion factor. If it is true that we are assuming too low of a CO-to-H_2 conversion factor for UGC 7636, then it is possible that the true upper limit on the H_2 mass is above the value required by the X-ray absorption explanation of the hole. (This would imply that our 30 hour observation was too short to detect the CO!) The possibilities that the CO-to-H_2 conversion factor is much higher in this system or that the X-ray absorption is due to dust without associated cold gas are discussed in the Sec. 4.

4. H_2 WITHOUT CO OR DUST WITHOUT COLD GAS?

In Sec. 3, we assumed a Galactic CO-to-H_2 conversion factor when calculating the upper limit on the mass of H_2 in the H I cloud. Recent theoretical work by Sakamoto (1996) indicates that the CO-to-H_2 conversion factor is fairly sensitive to the physical conditions within the system, at least for low density and/or low metallicity gas. He finds that for low density ($\lesssim 300$ cm^{-3}), low metallicity molecular clouds, the CO emission is optically thin and subthermal. Under these conditions, the CO-to-H_2 conversion factor, X, is related to the H_2 gas density, $n(H_2)$ and the CO abundance, Z(CO) as

$$X\approx X_o\left[\frac{n(\mathrm{H_2})}{300\ \mathrm{cm^{-3}}}\right]^{-1}\left[\frac{Z(\mathrm{CO})}{Z_\odot(\mathrm{CO})}\right]^{-1}, \tag{4}$$

and is only weakly dependent on temperature. Here, $Z_\odot$(CO) is the solar neighborhood abundance of CO. Thus, the value of X would be increased if either the density or CO abundance were reduced. While increasing X decreases the predicted CO flux, decreasing the abundance is not effective in this regard (Eq. (2)), at least if the CO abundance is proportional to the elemental abundance of oxygen and carbon. The reason is that the X-ray absorption is mainly due to the CO for molecular gas, and is also proportional to the abundance of CO. Thus, the only way to increase X and reduce the predicted CO flux is to reduce the density of the molecular gas. Thus, to reduce the predicted CO flux by at least two orders of magnitude would require

$$n(\mathrm{H_2})\lesssim 3\ \mathrm{cm^{-3}}. \tag{5}$$

A lower limit to the density in the molecular component of the X-ray absorber is given by the required mass divided by the volume, or equivalently, the required column density divided by the extent of the absorbing cloud along the line of sight. Assuming that the cloud's extent along the line of sight is equal to its narrower width in the plane of the sky gives a limit of

$$n(\mathrm{H_2})\gtrsim 0.4\left[\frac{Z(\mathrm{O})}{Z_\odot(\mathrm{O})}\right]^{-1}\left(\frac{d}{25.8\ \mathrm{Mpc}}\right)^{-1}\ \mathrm{cm^{-3}}, \tag{6}$$

which is not restrictive unless the abundance of oxygen is less than about one-eighth of solar.

As noted above, the primary source of soft X-ray opacity is the K absorption edge of oxygen. However, the absorption is nearly independent of the physical state of the oxygen, as long as it is not highly ionized. Thus, the absorption might be due to oxygen in dust grains. (An argument against this is that oxygen is only somewhat depleted onto interstellar grains in the solar neighborhood [de Boer 1981].) Thus, it would be possible to have soft X-ray absorption without any cold or cool gas if the grains were immersed in hot gas. For example, cold gas and associated dust might have been removed from UGC 7636, and the gas heated by shocks or thermal conduction. If the dust grains were not destroyed at the same time, one would find dust without much H I or H_2 gas. The dust grains would still be a significant source of soft X-ray absorption.

However, if the optical properties of the dust were similar to those in the solar neighborhood, the dust would also produce a visual extinction of $A_V \approx 4$ mag. Since this material must lie in front of the elliptical galaxy to produce the required X-ray absorption, this dust would produce a very strong extinction feature in the optical image of the galaxy. In fact, no such extinction feature is evident in the optical images of NGC 4472. To set a limit on the extinction (which will also turn out to be useful below), we examined an *R*-band CCD image of the galaxy taken with the Isaac Newton Telescope at La Palma and kindly provided by Brian McNamara (see M94 for the observing details). We compared the observed optical surface brightness in a circular aperture covering the H I cloud with the value for the same region from an elliptical isophotal model fit to the galaxy. To estimate the errors in the measured surface brightness, we repeated this procedure for many other regions of the same area at the same isophotal radius as the H I cloud. We find no evidence for any extinction at the position of the cloud, and we are able to place a very conservative upper limit of $A_V < 0.5$ mag (including systematic errors) on the visual extinction at this location.

Dust immersed in hot gas would be subject to destruction via thermal sputtering. Draine & Salpeter (1979) find that the time scale for sputtering, $t_{\rm sp}$, for dust in a plasma with temperature $T > 10^6$ K is

$$t_{\rm sp} = 10^8 \left[\frac{a}{10^{-5}\ \mathrm{cm}}\right] \left[\frac{n}{0.002\ \mathrm{cm}^{-3}}\right]^{-1} \mathrm{yr}\ , \tag{7}$$

where a is the radius of the dust grain and n is the number density of the plasma at the position of the cloud. At the projected radius of the cloud, the electron density of hot gas is $n_e \approx 0.002\ (d/25.8\ \mathrm{Mpc})^{-1/2}\ \mathrm{cm}^{-3}$ (IS96). If the cloud were removed from UGC 7636 near the center of NGC 4472 as predicted by IS96 (where the density of the halo is great enough to induce ram pressure stripping of the cloud), the sputtering time would be even shorter, since the cloud would have spent a portion of its time since removal in an environment with a considerably higher density. For comparison, if we assume that the cloud is at the projected distance from UGC 7636 and has been decelerated uniformly to its present position and velocity, we find that the cloud was removed from UGC 7636 approximately $2 \times 10^8\ (d/25.8\ \mathrm{Mpc})$ yr ago. Thus, dust grains with a typical size of 10^{-5} cm would have been destroyed by sputtering by now. Both the extinction and sputtering time arguments indicate that oxygen on dust grains is not responsible for the X-ray feature seen at the position of the H I cloud.

Finally, we consider the stability of the molecular hydrogen against dissociation from ultraviolet radiation from NGC 4472 and from the cosmic UV background. Using the relation of Federman *et al.* (1979), we can set a lower limit on the total hydrogen density ($n_{\rm crit} = n(\mathrm{H\,I}) + 2n(\mathrm{H_2})$) necessary for 10% of the hydrogen to turn molecular. This transitional region between H I and H_2 would occur in a shell surrounding the molecular gas. The critical density depends on the H I column density, $N(\mathrm{H\,I})$, which is observed to be $N(\mathrm{H\,I}) = 4 \times 10^{20}\ \mathrm{cm}^{-2}$ (M94). For the molecular gas temperature, we assume $T \approx 20$ K (e.g., O'Dea *et al.* 1994). We also assume the standard rate of formation of H_2 on dust grains of $G = 3 \times 10^{-18}\ \mathrm{cm}^3\ \mathrm{s}^{-1}\ \mathrm{K}^{-1/2}$ (van Dishoeck & Black 1986), although this almost certainly is an overestimate given the apparent lack of dust in the cloud. This point will be discussed below.

The other key parameter is the UV dissociation rate, χ, of H_2. The dissociation rate was estimated by calculating the respective contributions to the ultraviolet radiation field by NGC 4472 and the cosmic UV background. The main H_2 absorption bands occur in the wavelength region between 910 and 1000 Å, so we calculate the ultraviolet flux from both UV sources at 950 Å at the position of the cloud. Recent UIT observations of NGC 4472 by Ohl & O'Connell (1996) find that the galaxy has a total integrated magnitude of 14.1 within 45″ at 1500 Å. After assuming a blackbody spectrum with a temperature of 20,000 K as the source of the UV radiation [e.g., from extreme horizontal branch stars found in elliptical galaxies, see Brown *et al.* (1995)], the flux at 950 Å was calculated, and then converted to a flux at the projected distance of the H I cloud. Since the projected distance is the minimum value, this gives an upper limit on the UV flux from NGC 4472. The extragalactic ultraviolet flux was estimated by extrapolating the Vogel *et al.* (1995) value at 912 Å up to 950 Å using a $\nu^{-1.4}$ relation. We find that the flux from NGC 4472 is a factor of 3 larger than the extragalactic UV background flux. The sum of the UV fluxes from the two sources was calculated and χ was scaled from the de Jong *et al.* (1980) value to yield a value of $\chi = 3.3 \times 10^{-13}\ \mathrm{s}^{-1}$ for the dissociation rate within the cloud. With these parameters, the critical density becomes

$$n_{crit} = 2.8 \left[\frac{N(\mathrm{H\,I})}{4 \times 10^{20}\ \mathrm{cm}^{-2}}\right]^{-0.625} \left(\frac{T}{20\ \mathrm{K}}\right)^{-1/2} \times \left(\frac{G}{G_\odot}\right)^{-1} \left(\frac{\chi}{3.3 \times 10^{-13}\ \mathrm{s}^{-1}}\right) \mathrm{cm}^{-3}\ , \tag{8}$$

where $G_\odot$ is the H_2 formation rate in the solar neighborhood (van Dishoeck & Black 1986). This is a lower limit, since the rate of formation of H_2 on dust grains is probably much smaller due to the lack of dust in this cloud. Above, we derived an extremely conservative upper limit of $A_V < 0.5$ mag for the extinction of the cloud. Under these conditions, the H_2 formation rate would be about a factor of 20 smaller in the cloud as compared to the solar neighborhood. This would raise the H I density in the transitional region to over 50 cm^{-3}.

It is likely that the H I in the transitional shell and the molecular hydrogen just inside of this region are in pressure equilibrium. However, we will make the much more conservative assumption that the average density of all of the molecular gas is no lower than that of the outer H I gas. Note that if the outer gas and the molecular gas were in pressure equilibrium, and the molecular gas were colder, one would expect the molecular gas to be denser than the atomic gas. If the cloud is self-gravitating, the density contrast between the molecular and atomic gas would be increased further. Thus, it seems very likely that the average density of molecular hydrogen will exceed the critical density given by Eq. (8). If one includes the limit on the dust extinction and the resulting effect on the critical density, this implies $n(\mathrm{H}_2) \gg 3\ \mathrm{cm}^{-3}$. This is, at least, marginally inconsistent with the low molecular density required in Eq. (5) to reduce the excitation of the CO line below the observed limit. Thus, it is unlikely that absorption by molecular hydrogen is solely responsible for the X-ray feature.

5. CONCLUSIONS

We have searched for CO $J=1-0$ emission in the H I cloud between NGC 4472 and UGC 7636, but without success. This implies that either the decrease in X-ray surface brightness at the position of the H I cloud found in recent *ROSAT* observations is not the result of soft X-ray absorption by large amounts of molecular hydrogen, or that the CO-to-H_2 conversion factor in the cloud is at least two orders of magnitude larger than the Galactic value. We show that the latter could occur if the density of the molecular gas were as low as $n(\mathrm{H}_2) \lesssim 3\ \mathrm{cm}^{-3}$. However, if the density in the outer regions of the cloud is this low, the gas would not be dense enough to shield the H_2 gas from dissociation by UV. Soft X-ray absorption by dust also does not seem to be a viable explanation for the X-ray feature, particularly given the lack of an extinction feature at this projected position in NGC 4472.

Thus, it appears most likely that the X-ray hole is not due to X-ray absorption. The simplest explanation for this X-ray feature may be that the X-ray emitting gas in this region is hotter and less dense than the surrounding gas. As such, it could be in pressure equilibrium with the ambient gas. Reducing the density and increasing the temperature would produce a reduction in the X-ray surface brightness which is most evident for soft X-rays, as observed.

The CO observations indicate that the molecular content of the H I cloud is $\lesssim 3.3\times 10^7\ (d/25.8\ \mathrm{Mpc})^2\ M_\odot$, which is $\lesssim 10\%$ of the atomic gas mass, consistent with the results of Israel *et al.* (1995) for dwarf galaxies. It is also possible that only the H I gas has been stripped from UGC 7636. The initial molecular gas content of this dwarf galaxy may still be present in the galaxy, although if so it does appear to have been consumed in star formation triggered by the collision with NGC 4472 (M94).

Despite the fact that it appears that a significantly higher than Galactic CO-to-H_2 conversion factor does not explain the CO non-detection in this particular case, it is clear that several factors will influence the value of the CO-to-H_2 conversion factor in dwarf galaxies in general. Given the rather strong dependence of the CO-to-H_2 conversion factor on metallicity and density, the value of this conversion factor will remain uncertain until dwarf galactic properties are more accurately determined.

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