The dark cloud revisited

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INTERGALACTIC clouds are believed to be common in the remote Universe, but nearby examples are exceedingly rare. The best example of a large intergalactic cloud that is sufficiently close for there to have been extensive multifrequency studies is in the M96 group of galaxies towards Leo at a distance of about 10 megaparsecs. Stephen Schneider and collaborators¹ have now completed a detailed survey of the Leo intergalactic cloud. Their results, reviewed below, enable us to discuss whether such a cloud may indeed be a prototype of the intergalactic clouds that are studied at large redshift in absorption towards quasars.

The Leo cloud was originally discovered, by Schneider and co-workers², by means of its radio emission at 21-cm wavelength from atomic hydrogen (H I). There has since been a possible detection of ionized hydrogen (H II) in the cloud. However, searches for emission of visible light from the cloud have failed to find any evidence for an accompanying population of stars. Searches for emission from interstellar molecules and dust have similarly been negative. The Leo cloud is thus remarkable for an object of its mass in its very low level of star formation activity relative to the amount of gas present. For this same reason, other objects of this type will be difficult to find, but may constitute an important population in the Universe.

Ring structure

The 21-cm survey, performed at Arecibo and at the Very Large Array, has revealed that the H I gas in the Leo intergalactic cloud is distributed non-uniformly around a moderately eccentric ring of diameter 200 kiloparsecs (kpc); for comparison, the diameter of our Galaxy is 30 kpc. The ring's kinematics are those of a keplerian orbit of period 4×10^9 yr, whose centre coincides in position and velocity with the centroid of the M105/NGC3384 galaxy pair. Interestingly, the mass-to-light ratio for the pair implied by this is only $25M_{\odot}/L_{\odot}$ ($M_{\odot}$ and $L_{\odot}$ are the solar mass and luminosity), comparable to the value one expects for a purely stellar population, suggesting that there is little if any mass in a dark halo around the galaxies, and in contrast to what is found in many spiral galaxies, including our own. The total H I mass amounts to $2 \times 10^9 M_{\odot}$, and the mean density is only of the order of 10^{-3} cm^{-3} . However, high-resolution observations³ reveal that about half the H I is in clumps of size a few kiloparsecs, mass around $10^7 M_{\odot}$, velocity width about 20 km s^{-1} and central density 0.1 cm^{-3} . The virial masses of the clumps (deduced from their dynamics) seem to

exceed the H I masses by factors of 2–4; if this discrepancy is real, the balance could be supplied by envelopes of H II. The gravitational field of the central galaxy pair will tidally disrupt any gas cloud with a density less than 0.1 cm^{-3} , so the clumps appear to be marginally tidally stable.

A high-sensitivity search has been made for H α emission in the red spectral region from ionized hydrogen, with a sensitivity to an emission measure of about $1 \text{ cm}^{-6} \text{ pc}$ for gas at 10^4 K , tentative evidence for a detection at this level in the most dense parts of the cloud being reported⁴. The ionization rate required to account for the observed H α intensity is substantial, amounting to some 6×10^5 hydrogen ionizations per second per square-centimetre column through the clouds. If the H II gas fills most of the volume of the cloud, then its inferred mass exceeds that of the H I. If the gas is photoionized by an extragalactic ultraviolet background, the inferred ionizing flux is only a factor of 2–3 below what one infers by extrapolating from observational upper limits on this background in the 1,400–1,900-Å range⁵.

It is also possible that the ionization is produced by the ultraviolet hydrogen Lyman continuum radiation from OB stars, which might be expected to form in the more dense clumps of H I that are comparable in mass and mean density to dwarf galaxies. Sensitive optical observations of one of the most dense clumps show that the maximum surface brightness in the visible-band is $27.7 \text{ mag arcsec}^{-2}$. For comparison, note that for the galactic disk in the solar neighbourhood, the ionizing flux is estimated⁶ to be $3 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ for a visible-band surface brightness of $23.5 \text{ mag arcsec}^{-2}$ (ref. 7; brightness increases with decreasing magnitude). Assuming conservatively that the stars in the clump have the same distribution over mass and age as in the solar neighbourhood, the surface brightness inferred from the ionization rate would be only $27.8 \text{ mag arcsec}^{-2}$, compatible with the quoted upper limit. Given the uncertainties in the stellar mass function and age of the population, it seems that stellar photoionization provides the most natural explanation of the H α flux.

The disruptive tidal field may provide the reason for the inefficient star formation, as it would inhibit clumping of the gas. The clumps which do exist would be vulnerable to disruption by energy input from young stars if star formation were too vigorous. The distribution of the ring material around a single keplerian orbit suggests that it originated as a single weakly bound object which was then tidally disrupted on close approach to the

central galaxy pair — the tidal field being about 10 times stronger at the pericentre of the orbit than at the apocentre. The alternative possibility, that the ring is a shell of ejected gas, can be rejected on account of its negligible radial expansion. The time for the cloud to fall into the system, assuming initial conditions moving with the Hubble expansion of the Universe, would be roughly $6 \times 10^9 \text{ yr}$, so the ring material might only have orbited once in the age of the Universe.

Longevity

The ring owes its longevity to the relatively high angular momentum of the material in it: if it were on a more eccentric orbit, it might by now have been accreted onto the central galaxies. The existence of such material is a natural consequence of the tidal origin of galactic angular momentum in the gravitational-instability theory of galaxy formation, in which neighbouring condensations spin up one another. The dispersion in the angular momentum at fixed mass is predicted to be large⁸, and should result in some galaxies having reservoirs of outlying gas with high angular momentum.

One expects intergalactic clouds within groups of galaxies to be more common at earlier epochs, because the process of collecting material into galaxies would not have been 100 per cent efficient. This material would only gradually be exhausted as encounters occurred between clouds and galaxies. This late accretion of metal-poor gas could play a role in galactic chemical evolution. It is also tempting to speculate that some of the absorption lines seen in quasar spectra are produced by intergalactic clouds similar to that in Leo. The average H I column density seen in the cloud is a few 10^{18} cm^{-2} , comparable to that in metal-line absorption systems, and the velocity widths are also comparable⁹. The expected frequency of absorption lines would also turn out to be about right if most galaxy groups at large redshift contained clouds like that in Leo. Perhaps the dark H I cloud in Leo is a prototype of a more extensive population of intergalactic clouds that played a significant role in the early Universe. □

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- Schneider, S.E. *et al.* *Astr. J.* **97**, 666–673 (1989).
- Schneider, S.E., Helou, G., Salpeter, E.E. & Terzian, Y. *Astrophys. J.* **273**, L1–L5 (1983).
- Schneider, S.E., Salpeter, E.E. & Terzian, Y. *Astr. J.* **91**, 13–22 (1986).
- Reynolds, R.J. *et al.* *Astrophys. J.* **309**, L9–L12 (1986).
- Martin, C. & Bowyer, S. *Astrophys. J.* **338**, 677–706 (1989).
- Abbott, D.C. *Astrophys. J.* **263**, 723–735 (1982).
- de Vaucouleurs, G. & Pence W.D. *Astr. J.* **83**, 1163–1173 (1978).
- Barnes, J. & Efstathiou, G. *Astrophys. J.* **319**, 575–600 (1987).
- Sargent, W.L.W. in *Quasar Absorption Lines*, (eds Blades, C. & Norman, C.) 1–10 (Cambridge University Press, 1988).