THE ASTROPHYSICAL JOURNAL, 182:1–7, 1973 May 15

MARINER 9 ULTRAVIOLET SPECTROMETER EXPERIMENT: UPPER LIMITS ON THE LYMAN-ALPHA FLUX FROM CLUSTERS OF GALAXIES

RALPH C. BOHLIN
Department of Astro-Geophysics, and Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder

RICHARD C. HENRY*
Department of Physics, The Johns Hopkins University, and E. O. Hulburt Center for Space Research, Naval Research Laboratory

AND

J. R. SWANDIC†
The Johns Hopkins University
Received 1972 October 30

ABSTRACT

Data from the ultraviolet spectrometer on the *Mariner 9* Mars orbiter have been used to set upper limits on the redshifted Lα flux from the Perseus and Pegasus I (NGC 7619) clusters of galaxies. The limit for the Perseus cluster implies that the temperature of the intergalactic gas required for gravitational binding must be greater than 10^5 ° K, if it exists. A less severe limit is set for the Pegasus I cluster.

Subject headings: galaxies, clusters of — intergalactic medium — spectra, ultraviolet

I. INTRODUCTION

Certain clusters of galaxies give evidence of being unbound gravitationally, despite the great apparent age of individual galaxies in the cluster (Neyman, Page, and Scott 1961; Aarseth and Saslaw 1972). Perhaps the clusters are bound gravitationally by hot ionized gas which is too cool for profuse X-ray emission but too highly ionized for detection at 21 cm. Henry (1972) summarized the problem for the Coma cluster of galaxies. When combined with the X-ray observations of Meekins *et al.* (1971) and the theoretical work of Goldsmith and Silk (1971), his upper limit to the Lα recombination radiation strongly suggests that the Coma cluster is not bound gravitationally by intergalactic gas at any temperature. However, a reinterpretation of Henry's observation (King 1972; Friedman *et al.* 1972) and a revision of the calculations of Goldsmith and Silk (1972) do not restrict possible models quite so severely.

The study of Lα radiation from clusters of galaxies has been extended by using the ultraviolet spectrometer on the *Mariner 9* spacecraft. The spectrometer was used for astronomical observations for up to 2 hours per terrestrial day for 3 months after entering Mars orbit on 1971 November 13 (Lillie *et al.* 1972). Unfortunately, restrictions on the spacecraft attitude were such that the spectrometer could not be pointed at either the Coma or Virgo cluster of galaxies. Instead, two other clusters were chosen for investigation: Pegasus I (23^h18^m, $+8°$) and the Perseus cluster (3^h16^m, $+41°20'$). The radial velocities and wavelength shifts (3800 km s^{-1} and 15.4 Å for Pegasus; 5460 km s^{-1} and 22.1 Å for Perseus) are sufficient to distinguish any redshifted Lα radiation from Martian coronal Lα radiation. Like the Coma cluster, the Perseus

* Alfred P. Sloan Research Fellow.

† National Science Foundation Pre-Doctoral Fellow.

cluster is of particular interest because it is also an X-ray emitter (Fritz *et al.* 1971). Solinger and Tucker (1972) discussed the *Uhuru* X-ray satellite observations of these and other clusters of galaxies and concluded that the X-rays arise from thermal bremsstrahlung from a fraction of the binding mass of hot ($10^7\,°$–$10^8\,°$ K) intergalactic gas. However, Brecher and Burbidge (1972) argue for an origin by the process of Compton scattering of relativistic electrons (generated in radio sources present in each cluster) on the microwave background radiation. The present results argue against the presence of a binding mass of cooler ($10^5\,°$–$10^6\,°$ K) intergalactic gas but do not directly affect the discussion of the origin of the X-ray emission.

II. OBSERVATIONS

The *Mariner 9* ultraviolet spectrometer is an Ebert-Fastie monochromator with a collecting telescope of 29 cm^2 aperture. The entrance slit of the instrument projected on the sky is 0°.17 by 1°.2, giving a field of view of 6.2×10^{-5} sterad. Two channels record spectra that together cover the wavelength range 1150–3400 Å once every 3 seconds. Lα is recorded by the short-wavelength channel which scans from 1150 to 2000 Å in first order and 1150 and 1650 Å in second order. A more complete description of the instrument is in Pearce *et al.* (1971).

On 1972 January 19 and 24, respectively, 2324 spectra of the Pegasus I cluster and 1939 spectra of Perseus were received at the Goldstone antenna. Each set of data from the short-wavelength channel was averaged to minimize the effects of cosmic rays and other system noise. The resulting spectra were smoothed by using a sliding two-point average so that every other point is totally independent. Since the spectrometer sampled about three times per resolution element, the smoothing did not significantly degrade the resolution.

Figure 1 illustrates the procedure used to derive upper limits on the shifted Lα in the case of the Pegasus I cluster. The ordinate is the response in instrumental units, a measure of photomultiplier current. An offset of 6.4 units was superposed on the signal to allow for possible zero-point drift. This offset has already been subtracted from the data shown in figure 1*a*. The local Lα signal marked as 1216 Å in both first and second orders is off-scale on this figure. The solid curve is an approximate fit of an exponential to the residuals. This decay is a transient caused by turning on the high voltage at the beginning of each 3-second scan. Using an expanded ordinate after subtracting the exponential, figure 1*b* depicts a least-squares fit of a fourth-order polynomial to the residuals, excluding the Lα signal. In order to determine the appropriate zero level for a discrete, weak emission line that might be present at the redshifted wavelength of Lα in the observed clusters of galaxies, the polynomial fit was subtracted from the residuals (fig. 1*c*).

The position in the spectra of a Lα line with a known velocity shift is precisely determined by the local Lα emission and the spectrometer dispersion. The instrumental profile is approximately triangular with a full width at half-maximum of 15 Å in first order and 7.5 Å in second order. The assumption that an intergalactic emission line has a width equal to the observed velocity dispersion of the galaxies determines the expected shape of the Lα profile.

A least-squares fit of the galactic profile at the redshifted wavelength was found for the second-order data of figure 1*c* and the corresponding data for the Perseus cluster. The second-order data are preferable because six (Pegasus) and eight (Perseus) sample points of the profile are resolved from the unshifted local emission. The flux values for the fits to the resolved points (figs. 2 and 3) are 17 (Pegasus) and 14 (Perseus) photons cm^{-2} s^{-1} for sources entirely within the field of view. Although both clusters give a positive result, these measurements are probably not real signals because of the noise level of the data. The dispersions for groupings of six points in Pegasus I and eight points in Perseus for the 450 samples not near Lα were computed. The upper

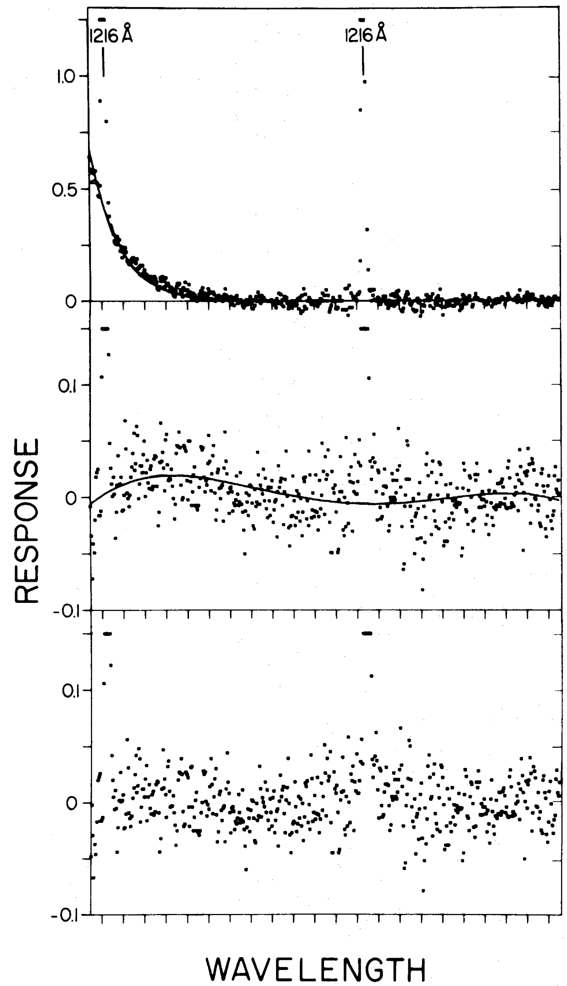

FIG. 1.—Observed spectrum for the Pegasus I cluster. The first- and second-order local Lα is marked. Each division on the abscissa is 100 Å in first order. (*a*) (*top*).—Average of 2324 spectra with a constant offset of 6.40 subtracted. *Solid line*, an exponential fit to the data points. (*b*) (*center*).—The data on an expanded vertical scale after subtracting the exponential. *Solid line*, a least-squares fit of a fourth-order polynomial to the data points. (*c*) (*bottom*).—The data with the corrected zero level after subtracting the polynomial.

limits at the 3 σ level for this random noise correspond to 23 (Pegasus) and 24 (Perseus) photons cm^{-2} s^{-1} from sources in the slit. These values are the observational upper limits. A correction must be made (see discussion below) for interstellar absorption in the Galaxy, for motion of the slit in the sky, and for overfilling of the slit. None of the resolved points in first order (three for Pegasus I and five for Perseus) lie above the response expected from the best fit to the second-order data, so the upper limits quoted above are probably safe near the 3 σ level, even considering uncertainties in the absolute calibration.

III. DISCUSSION

The flux of redshifted Lα photons is given by

$$F(\mathrm{L}\alpha) = \frac{\alpha(T)N_e^2}{4\pi R^2 fV} , \qquad (1)$$

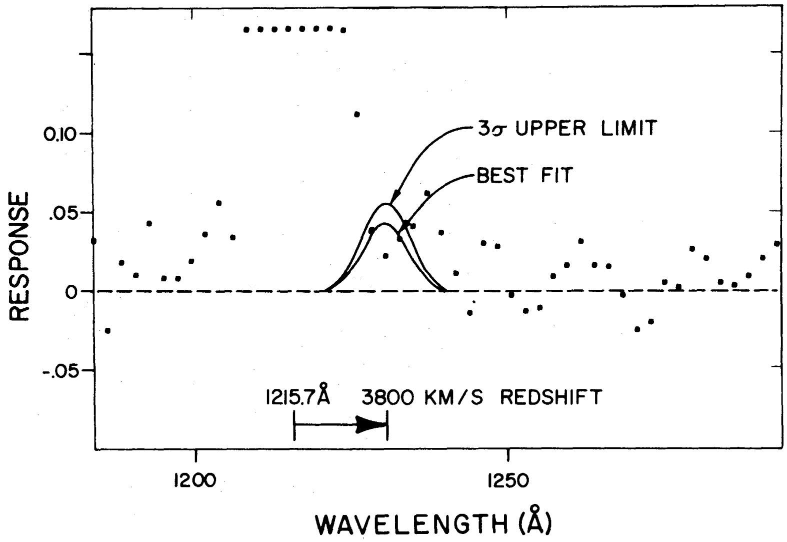

FIG. 2.—Best fit and upper limit of shifted Lα for the Pegasus I second-order data. The eight points at the top of the figure are the off-scale local Lα signal.

where $\alpha(T)$ is the temperature-dependent recombination coefficient effective in producing Lα quanta, N_e is the total number of electrons in the postulated hot intergalactic clouds, R is the distance to the cluster, V is the total volume of the cluster, and f is the fraction of that volume occupied by clouds of ionized gas (Henry 1972). The observed Lα upper limits are used to obtain limits on f as a function of temperature, on the assumption that a binding mass of gas is present.

a) *The Pegasus I Cluster*

The dynamics of the five brightest members of the Pegasus I cluster have been investigated by Hodge (1961). Mass-to-light ratios on the order of 300 for the elliptical galaxies in the group were obtained, assuming that the galaxies themselves provide the binding mass. This is a factor of 4 greater than commonly observed and suggests

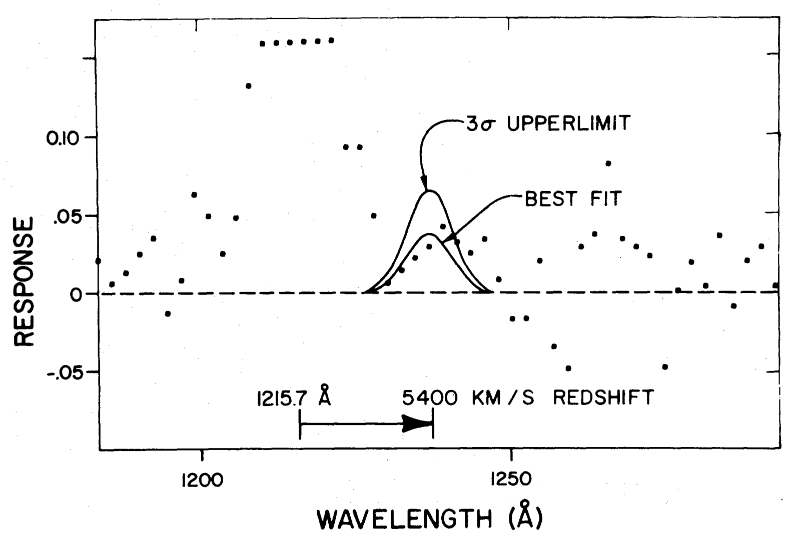

FIG. 3.—Best fit and upper limit of shifted Lα for the Perseus second-order data

the possibility that the group is bound by large amounts of hot gas. The mean radial velocity of the group, 3800 km s^{-1}, corresponds to a distance of 72 Mpc if the Hubble constant $H = 53$ km s^{-1} Mpc^{-1} (Sandage and Tamman 1972). The value used for H is critical because the flux depends on H^3. Hodge performed a virial-theorem analysis under a number of assumptions, obtaining a minimum mass of 2.09×10^{13} $M_\odot$ using $H = 75$. For $H = 53$ the mass becomes 2.96×10^{13} $M_\odot$. If essentially all of this mass is in the form of ionized hydrogen, then $N_e = 3.54 \times 10^{70}$ electrons. Visual inspection of a *Palomar Sky Survey* plate (fig. 4*a* [plate 1]) indicates that the cluster is centered near NGC 7619 and is roughly circular with a 0°.5 diameter and a spherical volume of 3.8×10^{72} cm^3. The nominal orientation of the *Mariner 9* slit is shown on the figure as solid lines, and the dashed lines illustrate the extent of motion of the field of view caused by the ±0°.25 limit cycle of the spacecraft attitude control system.

The observed upper limit on the mean flux is 23 photons cm^{-2} s^{-1}. Because of the limit cycle and narrow slit width, the observational limit must be multiplied by a factor of 4 to obtain the upper limit on the total flux from Pegasus I. Taking 2 as the absorption factor at the galactic pole, noting that Pegasus I is at galactic latitude $b = 48°$ S, and assuming a cosec b dependence of the absorption, another factor of 2.5 allows for interstellar absorption of Lα by dust. The final upper limit on the redshifted Lα flux from the whole cluster is 230 photons cm^{-2} s^{-1}.

Substituting the limits into equation (1) with the effective recombination coefficient, $\alpha(T)$, computed following Goldsmith and Silk (1972), we obtain the relation between the clumpiness, C ($=1/f$), and T shown in figure 5. Goldsmith and Silk assumed that one-half of the total recombinations to $n \geq 2$ leave the atom in the $2p$ state and produce a Lα photon. They also include collisional excitation of Lα in $\alpha(T)$, an important effect for $T < 10^5$ ° K. The points in the figure representing the actual condition of the Pegasus I cluster (if one assumes that a binding mass of gas is present) must lie below the indicated sloping line.

b) *The Perseus Cluster*

The Lα limit for the Perseus cluster provides further evidence that this cluster may not be bound gravitationally, despite the high density of galaxies that apparently form an interacting group. The chain of galaxies dominating the general appearance indicates that the cluster may not be relaxed. The large velocity dispersion of 1420 km s^{-1} implies a virial mass of 1.4×10^{15} $M_\odot$ (for $H = 53$), at least a factor of 100 greater than the mass of the observed member galaxies (Chincarini and Rood 1971, referred to as CR). CR found an average radial velocity of 5460 km s^{-1}, corresponding to a distance of 103 Mpc. The *Mariner 9* slit was oriented along the major chain of galaxies, but it is still difficult to decide how much of the cluster mass was actually within the field of view drawn on figure 4*b*. If NGC 1265 is bound, then the matter providing the binding force is most effective when located closer to the center of mass of the cluster than is this galaxy. Therefore, a spherical model of the Perseus cluster is constructed with a center at NGC 1275 and a radius of 0°.45, equal to the separation of the two galaxies. This is the conservative model A with a volume of 6.4×10^{73} cm^3. In contrast, for a "liberal" model B all the "virial" mass is assumed to be concentrated in the string of galaxies located in the right half of the slit in figure 4*b*. We assume that the cluster is a disk 0°.17 in height and 0°.60 in diameter with a volume of 8.2×10^{72} cm^3.

The observed upper limit on the flux is 24 photons cm^{-2} s^{-1}. To allow for overfilling of the slit and the motion of the limit cycle during the observation, factors of 4.9 for model A and 3.4 for model B are necessary. The absorption by interstellar dust is severe, a factor of 18, due to the low (14° S) galactic latitude of the cluster. The upper limits to the redshifted Lα flux from the whole cluster are 2000 (A) and 1400 (B) photons

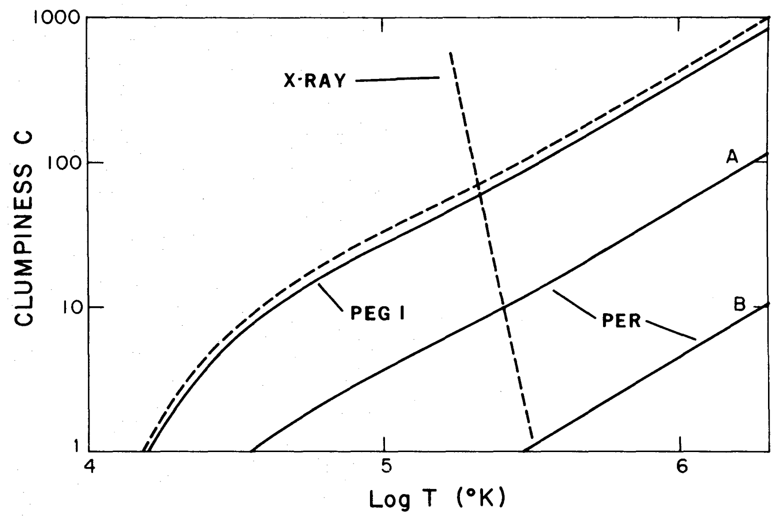

FIG. 5.—The clumping parameter $C\ (=1/f)$ versus temperature. Dashed lines are for the Coma cluster of galaxies (Friedman *et al.* 1972). The negatively sloping dashed line is an X-ray upper limit on C. The positively sloping lines are upper limits derived from the flux limits on the red-shifted Lα. *Solid lines*, the limits for Pegasus I and Perseus, models A and B.

$\text{cm}^{-2}\ \text{s}^{-1}$. Photometry for NGC 1275 (de Vaucouleurs and de Vaucouleurs 1964) suggests that absorption by dust may be abnormally low, so these upper limits are conservative.

Limits on the clumping parameter C are obtained for the two models by substituting the above numbers into equation (1). Figure 5 shows the severe restrictions of the temperature and degree of clumping of a hypothetical binding mass of hot gas at temperatures less than $\sim 10^6\ ^\circ$ K. There is uncertainty in both estimating the "virial" mass and determining the extent of the cluster, so the limit must be treated with a degree of caution.

The Perseus cluster is a known X-ray source. If the X-ray intensity (Solinger and Tucker 1972) is substituted in the bremsstrahlung formula (Allen 1963), an upper limit for the temperature of $\sim 10^7\ ^\circ$ K is obtained, because the brightness of the Perseus cluster in X-rays is so great. Radiation from small amounts of hotter gas (or from the inverse-Compton process) masks thermal radiation from a binding mass of cooler gas ($10^6\ ^\circ$–$10^7\ ^\circ$ K), if such exists. A soft X-ray spectrum of the Perseus cluster is the most sensitive observation that could determine if the binding mass exists in this temperature range.

IV. CONCLUSIONS

Observations with the ultraviolet spectrometer on the *Mariner 9* Mars orbiter were used to set limits on the temperature and the degree of clumping of binding masses of hot intergalactic gas in the Pegasus I and Perseus clusters of galaxies. The observational limits in the case of the Pegasus I cluster are not stringent. For the Perseus cluster, severe restrictions are placed on the clumping and the temperature of any binding mass of hot gas. The Lα measurement sets a lower limit of $\sim 10^5\ ^\circ$ K, and the X-ray observation requires $T \leqslant 10^7\ ^\circ$ K. Very soft X-ray observations or more sensitive Lα measurements could be used to completely rule out the possibility that the Perseus cluster is gravitationally bound by hot intergalactic gas.

These observations were made possible through the efforts of C. A. Barth and other members of the *Mariner 9* team at the Laboratory for Atmospheric and Space Physics and the Jet Propulsion Laboratory. This research was sponsored by the National Aeronautics and Space Administration.

REFERENCES

Aarseth, S. J., and Saslaw, W. C. 1972, *Ap. J.*, **172**, 17.
Allen, C. W. 1963, *Astrophysical Quantities* (London: Athlone Press).
Brecher, K., and Burbidge, G. R. 1972, *Nature*, **237**, 440.
Chincarini, G., and Rood, H. J. 1971, *Ap. J.*, **168**, 321.
Friedman, H., Fritz, G., Shulman, S. D., and Henry, R. C. 1972, *IAU/COSPAR Symposium on X- and Gamma Ray Astronomy* (*Non-solar*) (Dordrecht: Reidel Publishing Co.) (in press).
Fritz, G., Davidsen, A., Meekins, J. F., and Friedman, H. 1971, *Ap. J.* (*Letters*), **164**, L81.
Goldsmith, D. W., and Silk, J. 1971, *Bull. A.A.S.*, **3**, 437.
———. 1972, *Ap. J.*, **172**, 563.
Henry, R. C. 1972, *Ap. J.* (*Letters*), **172**, L97.
Hodge, P. W. 1961, *Ap. J.*, **134**, 262.
King, I. R. 1972, *Ap. J.* (*Letters*), **174**, L123.
Lillie, C. F., Bohlin, R. C., Molnar, M. R., Barth, C. A., and Lane, A. L. 1972, *Science*, **175**, 321.
Meekins, J. F., Fritz, G., Chubb, T. A., Friedman, H., and Henry, R. C. 1971, *Nature*, **231**, 107.
Neyman, J., Page, T. L., and Scott, E. 1961, *A.J.*, **66**, 533.
Pearce, J. B., Gause, K. A., Mackey, E. F., Kelly, K. K., Fastie, W. G., and Barth, C. A. 1971, *Appl. Opt.*, **10**, 805.
Sandage, A. R., and Tammann, G. A. 1972, *Ann. Rept. Hale Obs. 1970–1971.*
Solinger, A. B., and Tucker, W. H. 1972, *Ap. J.* (*Letters*), **175**, L107.
Vaucouleurs, G. de, and Vaucouleurs, A. de. 1964, *Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press).