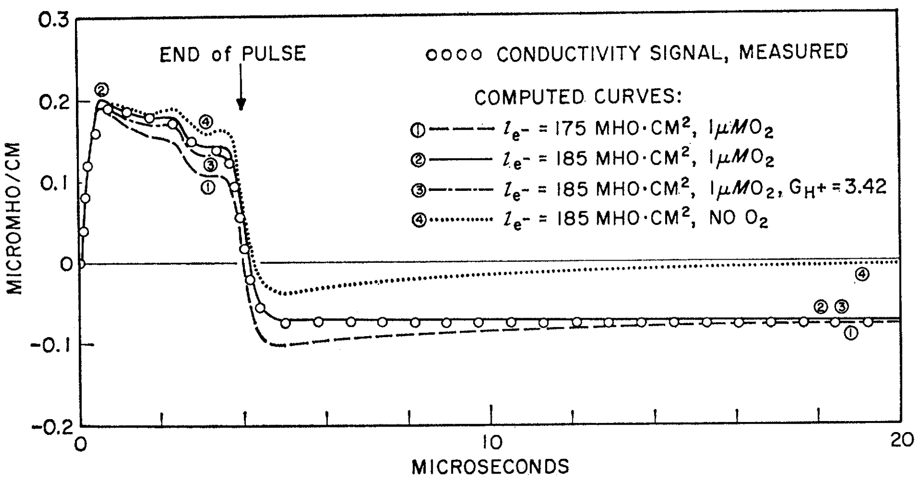

Fig. 2. Transient conductivity signal, obtained by irradiating a $Ba(OH)_2$ (about 4 $\times$ 10^{-5} N) solution with a 4-μsec pulse of electrons at an average dose rate of 4 $\times$ 10^{25} ev liter^{-1} sec^{-1}, and several computed signals.

reversals. For each measurement, two oscilloscope pictures at different battery polarities were taken. Since the nonbalanced portion of the charge-induced signals was independent of cell voltage, the "pure" conductivity signal could be derived by algebraical subtraction of the signals in the two pictures.

Figure 2 shows the conductivity signal (circles) obtained by subtracting two such traces. For evaluating the results, a CDC-3600 digital computer was used. A computer program had been written so that the concentrations of all chemical species involved and the change in conductivity as functions of time could be calculated from (i) the G-values for the molecular and radical products of water radiolysis; (ii) the rate constants for the reactions of these products with each other, published values (*9*), mostly determined by optical pulse-radiolysis techniques, being used; (iii) the mobilities of all ionic species (in this case the known values for H_3O^+ and OH^- and assumed values for e^-); (iv) the dose rate as a function of time, approximated by successive step functions.

Several conductivity signals thus computed are included in Fig. 2. As can be seen in this figure, the signals become negative after the pulse, an indication of transient decrease in conductivity which can be explained by a mobility of the electrons less than that of OH^-. The negative portion is strongly influenced by impurities such as O_2 which scavenge electrons and form negative ions of lower mobility (such as O_2^-). In order to fit the measured and the computed curve, we had to assume an oxygen content of the solution of 1 μM (compare curves No. 2 and No. 4). On the other hand, the positive portion depends strongly on electron mobility (compare curves No. 1 and No. 2), but relatively little on above-mentioned impurities, so that this portion was used as a criterion for the mobility. In order to show the influence of the H_3O^+ yield, about which there still is some uncertainty, we have also computed a curve for $G_{H_3O^+} = 3.42$ (5 percent lower than the value assumed to be correct) and correspondingly $G_{OH^-} = 0.82$ (curve No. 3). In Fig. 2 the best fit was obtained with curve No. 2, indicating an equivalent conductance, l_{e^-}, equal to 185 mho cm^2. Other measurements yielded slightly different values. As average values, we obtained for the hydrated electron the following results: the equivalent conductance, l_{e^-}, was 177 mho cm^2 $\pm$ 10 percent (*10*); the mobility ($\mu_{e^-} = l_{e^-}/F$, where F is the Faraday constant), μ_{e^-}, was 1.84 $\times$ 10^{-3} cm^2 volt^{-1} sec^{-1} $\pm$ 10 percent; the diffusion constant, D_{e^-} = 4.75 $\times$ 10^{-5} cm^2 sec^{-1} $\pm$ 10 percent. These values are about half the values previously estimated by Schwartz (*11*) and Platzman (*3*). Matheson (*2*) has used our value of the diffusion constant for calculating the diffusion-controlled rate constant for the reaction of the hydrated electron with oxygen, at the same time using an electron radius of 2.7 Å (*12*) and a radius for O_2 of 1.6 Å (*13*). The value obtained (2.33 $\times$ 10^{10} M^{-1} sec^{-1}) is consistent with the experimental value of 2 $\times$ 10^{10} (*9*).

KLAUS H. SCHMIDT
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60440
WARREN L. BUCK
Solid State Science Division

References and Notes

1. E. J. Hart, *Science* **146**, 19 (1964).
2. M. S. Matheson, *Advance. Chem. Ser.* **50**, 45 (1965).
3. R. L. Platzman, in "Physical and chemical aspects of basic mechanisms in radiobiology," *Nat. Acad. Sci., Nat. Res. Council* Publ. No. 305 (1953), p. 22.
4. A. Kupperman, in *Actions chimiques et biologiques des radiations, V^e série*, M. Haissinsky, Ed. (Masson, Paris, 1961), p. 87.
5. After an estimate by M. S. Matheson, based on the assumption that all H is produced by the reaction $e^- + H^+$ in the spurs.
6. C. B. Senvar and E. J. Hart, *Proc. Intern. Conf. on Peaceful Uses of Atomic Energy, 2nd, Geneva*, **29**, 19 (1958).
7. The spontaneous oxidation of the solution catalyzed by the platinum foils was taken into account by using as blanks unirradiated samples which had been in the cell for the same time as the corresponding irradiated samples. The Fe^{3+} yields measured by Thomas and Hart (*8*) were used.
8. J. K. Thomas and E. J. Hart, *Radiation Res.* **17**, 408 (1962).
9. L. M. Dorfman and M. S. Matheson, *Progr. Reaction Kinetics* 3, 237 (1965)
10. The error limit of 10 percent does not include uncertainties in the G-values and rate constants used for computation. However, a given relative error in any one of these quantities would only cause a considerably smaller error in mobility.
11. H. A. Schwarz, *Radiation Res. Suppl.* **4**, 89 (1964).
12. J. Jortner, *ibid.* **4**, 24 (1964).
13. L. Pauling, *The Nature of the Chemical Bond* (Cornell Univ. Press, Ithaca, N.Y., ed. 3, 1960), p. 518.
14. Based on work performed under the auspices of the U.S. Atomic Energy Commission.

27 September 1965

A Search for Intergalactic Hydrogen in the Virgo Cluster

Abstract. *A fixed-horn antenna having a beam 10° by 10°, and a switched-load radiometer with traveling-wave-maser preamplifier were used to observe the 21-cm spectrum of the Virgo cluster of galaxies. An upper limit to the antenna temperature is 0.024°K relative to regions outside the cluster with filters whose width is 2 Mc/sec. If the excitation temperature of the intergalactic hydrogen is enough greater than the background continuum radiation so that absorption can be ignored, and if the velocity spectrum is that defined by the galaxies, the density of optically thin neutral hydrogen in the cluster does not exceed that outside of the cluster by an amount that gives 5.6 $\times$ 10^{12} solar masses in the cluster.*

Whether or not clusters of galaxies contain large masses of intergalactic material is an open question. See, for example, the opposing views of van den Bergh (*1*) and Holmberg (*2*). If this intergalactic material exists, it might be in the form of ionized hydrogen (*3*) or in another form. However, if the material is neutral atomic hydrogen, it may

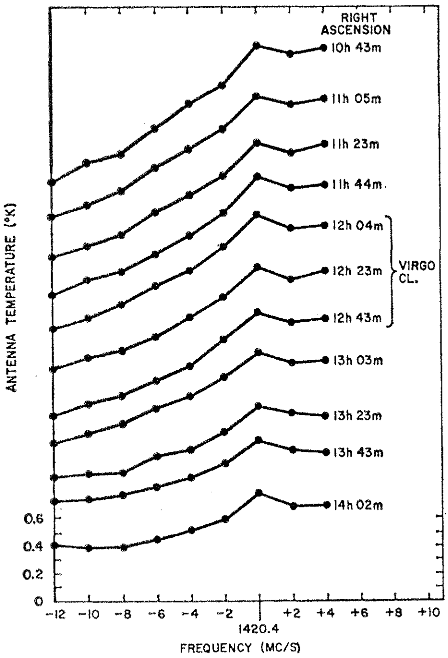

Fig. 1. The 21-cm spectra at declination + 13°, and various right ascensions that include the Virgo cluster.

be detectable from its 21-cm line radiation. Muller (*4*) observed the 21-cm spectrum of the Coma cluster, and set an upper limit of 3×10^{12} solar masses for the optically thin neutral hydrogen in a 0.25 square-degree field which contains 9×10^{13} solar masses of galaxies.

The Virgo cluster is less compact and contains a greater percentage of spiral galaxies than the Coma cluster. Robinson, van Damme, and Koehler (*5*) have observed 21-cm absorption in the spectrum of Virgo A (NGC 4486, a member of the cluster) with a velocity of 1100 km/sec. They have also set an upper limit of 0.2°K to the emission at this velocity from a point 1° away from Virgo A. They argued that the gas they observed is certainly in the Virgo cluster because of its velocity; but probably it is not in Virgo A, because the intense continuum radiation of the elliptical galaxy would ionize the gas or at least raise the excitation temperature enough to make it a poor absorber. Observations by Epstein (*6*) corroborate the absorption in the spectrum of Virgo A. Robinson, van Damme, and Koehler used a receiver that measured the difference of power in two frequency bands 3 Mc/sec or 633 km/sec apart. Hydrogen lines that have widths larger than this frequency spacing cannot be observed with such a receiver. We now describe an attempt to improve on the earlier observations in two ways: (i) with a small antenna whose beam averages the emission from nearly all the cluster leads to a mass of neutral hydrogen in the whole cluster rather than that in an individual cloud; (ii) with a switched load receiver that allows detection of lines having half-power widths up to about 8 Mc/sec or 1690 km/sec with full sensitivity.

The antenna is a pyramidal horn with aperture 1.08 by 1.44 m, mounted in the meridian plane, fixed at declination +13°. The beamwidth is 10° in both right ascension and declination, and the calculated collecting area is 1.1 m^2. The receiver has a circular switch at the input to compare the temperature of the antenna to that of a coaxial resistor in liquid nitrogen.

The coaxial line between the antenna and switch is intentionally lossy so that the input temperature differs less than 5°K from the temperature of the reference load, 80°K. The system noise temperature is 140°K. The traveling wave maser has been described (*7*). The receiver has five filters of 2 Mc/sec width in simultaneous use. The filters are spaced 2 Mc/sec and each operates a detector, phase detector, and integrator. A scanning digital voltmeter records the integrated output voltages, and these voltages are expressed in terms of antenna temperatures with the aid of calibration signals applied from an argon noise source through a directional coupler on the antenna side of the switch.

Observations are made in two frequency bands arranged to give one overlapping point. Half of the observations are made with the receiver local oscillator frequency above the signal frequency and half with the local oscillator frequency below. When the two halves are combined, the results are less affected by "channel number effect," the tendency for an individual filter, detector, phase detector, and integrator to give a reading that is consistently higher or lower than the others.

Figure 1 shows 11 consecutive spectra where each point represents 4 minutes of integration. The interstellar gas in the galaxy gives the emission line at 1420.4 Mc/sec. The theoretical root-mean-square (rms) fluctuations (*8*) are 0.013°K, but the spectra in Fig. 1 have a characteristic nonlinear shape that cannot be due to these theoretical fluctuations. Although the origin of the characteristic shape has not been explained, some possible causes are: (i) residual channel number effect, (ii) the frequency dependence of the ohmic

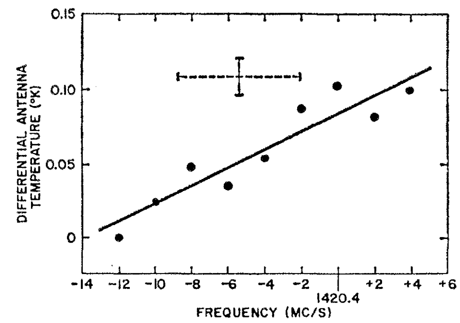

Fig. 2. Average of three spectra with the Virgo cluster in the antenna beam minus the average of six spectra taken before and after the transit. The spectra with right ascensions 11^h 44^m and 13^h 03^m have been omitted. The vertical bracket shows the adopted upper limit to the antenna temperature; and the horizontal bracket shows the effective width of the velocity spectrum of the galaxies.

losses of the antenna and its transmission line, and (iii) man-made radio signals. The characteristic shape of the spectra constitutes a large uncertainty in detecting a general distribution of intergalactic gas, but not in determining the relative density of gas in adjoining positions in the sky, because it changes slowly with time. In Fig. 2, the first three and last three spectra have been averaged and subtracted from the average of the three spectra that were measured when the Virgo cluster was in the antenna beam. The continuum radiation from Virgo A is calculated to produce an antenna temperature of 0.08°K; but the drifts of the radiometer made it impossible to detect a signal, of this intensity, which affects all channels. The absorption of 0.005 (*5*) would decrease the points measured at −4 and −6 Mc/sec in Fig. 2 by 0.0002°K, an amount far too small to be detected.

The following expression for the neutral hydrogen mass M of an optically thin emitter that is much smaller than the antenna beam follows from a result of Wild (*9*)

$$M = (1.38 \times 10^{-7} T_a \Delta\nu r^2)/A_a \quad (1)$$

where M is in solar masses, T_a is the peak antenna temperature in degrees Kelvin, $\Delta\nu$ is the effective line width in cy/sec, r is the distance in parsecs, and A_a is the antenna-collecting area in square meters. This formula is based on the assumption that the excitation temperature of the neutral hydrogen is much larger than the background-continuum radiation, so that absorption by the gas is negligible compared to the emission.

Since the size of the Virgo cluster is comparable to the 10° by 10° beam of the horn antenna, a correction to Eq. 1 is needed because gas in the outer part of the antenna beam makes a smaller contribution to the antenna temperature than that in the center. This correction is determined from de Vaucouleurs' (*10*) plot of 212 galaxies in the region of the cluster and from a superimposed, calculated antenna pattern. If the distribution of gas is the same as that of the galaxies, then the sum of the relative antenna power responses for each galaxy divided by the number of the galaxies is the fractional reduction in antenna temperature that would be produced by moving the gas from the center of the antenna beam to the positions of the galaxies. The fractional reductions obtained at the three right ascensions are 0.284, 0.470, and 0.373. The right-hand side of Eq. 1 must be multiplied by the mean of the reciprocals of these fractional reductions or 2.78. Applying this correction and substituting the values $r = 10^7$ parsecs and $A_a = 1.1$ m^2 gives the formula

$$M = 3.47 \times 10^7 \, T_a \, \Delta\nu \qquad (2)$$

which is applicable to the present observations of the Virgo cluster. If the hydrogen atoms have the same velocity spectrum as the galaxies in the cluster, the observed optical red shifts serve to estimate the form of the velocity spectrum. The measurements of Humason, Mayall, and Sandage (*11*) contain velocities for 45 galaxies within 5° of the adopted center $12^h\ 28^m$, +13°. For these 45 galaxies the mean velocity of recession is 1130 km/sec or 5.4 Mc/sec while the effective width of the velocity spectrum is 1400 km/sec or 6.7 Mc/sec. Figure 2 does not show the presence of line emission from the cluster. The rms deviation of the nine points from a least-squares straight line is 0.012°K. I adopt twice this value as an upper limit to the antenna temperature caused by line emission from the cluster. Substitution of 0.024°K for T_a and 6.7 Mc/sec for $\Delta\nu$ into Eq. 2 yields 5.6×10^{12} solar masses as an upper limit to the atomic hydrogen in the Virgo cluster. For comparison, Holmberg (*2*) has obtained 3.1×10^{13} solar masses for the galaxies in the cluster, an estimate based on luminosities.

In conclusion, if the excitation temperature of the neutral hydrogen atoms in the Virgo cluster is much greater than the background continuum radiation, and if the angular distribution and velocity spectrum of the hydrogen are similar to those of the galaxies, then the mass of optically-thin neutral hydrogen does not make an important contribution to the dynamics of the cluster. If one takes the Virgo cluster to be a sphere whose center is 10^7 parsecs away and whose radius subtends an angle of 5°, a uniform density of 8.1×10^{-5} hydrogen atoms/cm^3 is equivalent to the upper limit found above. This density is about one order of magnitude higher than upper limits (*12*) that have been found for the density of neutral hydrogen atoms in the general intergalactic medium.

SAMUEL J. GOLDSTEIN, JR.
Leander McCormick Observatory, University of Virginia, Charlottesville

References and Notes

1. S. van de Bergh, *Astron. J.* **66**, 566 (1961).
2. E. Holmberg, *ibid.* **66**, 620 (1961).
3. F. D. Kahn and L. Woltjer, *Astrophys. J.* **130**, 705 (1959); see also T. Gold and F. Hoyle, in Paris Symposium on Radio Astronomy (Stanford Univ. Press, Stanford, Calif., 1959), p. 583.
4. C. A. Muller, *Bull. Astron. Soc. Netherlands* **14**, 339 (1959).
5. B. J. Robinson, K. J. van Damme, J. A. Koehler, *Nature* **199**, 1176 (1963).
6. E. E. Epstein, *Astron. J.* **69**, 490 (1964).
7. E. B. Treacy and M. L. Hensel, *Rev. Sci. Instr.* **35**, 970 (1964).
8. The theoretical rms fluctuations are calculated from a formula given by R. S. Colvin, thesis, Stanford University, Stanford, Calif. 1961, p. 53.
9. J. P. Wild, *Astrophys. J.* **115**, 206 (1952).
10. G. de Vaucouleurs, *Astrophys. J. Suppl. Ser. 56*, **6**, 213 (1961).
11. M. L. Humason, N. U. Mayall, A. R. Sandage, *Astron. J.* **61**, 97 (1956).
12. G. B. Field, *Astrophys. J.* **135**, 684 (1962); S. J. Goldstein, Jr., *ibid.* **138**, 978 (1963).
13. The observations reported here were made at the G. R. Agassiz Station of Harvard College Observatory and were supported by NSF. I thank D. P. Smith for construction of parts of the apparatus and for assistance with the observations, and Prof. A. E. Lilley for permission to use the facilities of the Agassiz Station.

1 November 1965

Gravitational Lens Effect: An Observational Test

Abstract. *The large proper motion of the nearby star 40 Eridani-A will pass a distant star in 1988. It should be possible to observe the gravitational lens effect of this eclipse by existing photoelectric methods.*

In 1936, Einstein, in response to a suggestion by R. W. Mandl, reported that a nearby star passing in front of a distant one could create a lens-like effect which would intensify the image of the distant star (*1*). Some recent review papers by Liebes (*2*), Refsdal (*3*), and others have reopened discussion of the direct observation of this effect. Refsdal states that such events should occur rather frequently, and Liebes calculates that "as a consequence of the gravitational lens-like action of one star, it is possible for the image of another more distant star within our galaxy to be intensified by a factor in excess of 1000." However, there seems to be no record of any such event having been actually observed.

Because of the possibility that I (or the observatory) may not be around in 1988, it is the purpose of this report to draw attention to a possibly observable stellar eclipse that would be suitable for verifying the gravitational lens effect. During a study of double stars with large proper motions, carried out over the past 5 years with the 30-inch (75-cm) refractor at Allegheny Observatory, a star of about magnitude 15 was found directly in the path of 40 Eridani-A. The system 40 Eri consists of three stars—the pair BC has a period of about 250 years and revolves around A in about 8000 years (*4*). The proper motion of 40 Eri-A is 4.082″ in position angle 212.6°. If the background star X has no appreciable proper motion of its own (whether it does can be checked easily during the next 10 years), then the motion of 40 Eri-A will take it directly over the position of X in 1988; the resulting eclipse may be utilized to determine the gravitational lens effect (Fig. 1).

The distance and spectral type of star X are not known, but comparison of blue and red plates indicates that it is a normal star. For the rest of the discussion it is assumed to be a solar-type star at a distance of 1000 light years. The choice of 40 Eri-A is fortuitous since the parallax, spectral types, and masses of the three components are accurately known. [It is interesting to note but of no direct concern in this discussion that star B is the best-observed white dwarf for which the relativistic red shift has been accurately determined by Popper (*5*).]

Liebes shows that when a distant object star, *O*, lies directly in the path of a nearer star, *D*, called the deflector, the image of *O* undergoes a transformation, splitting into two ellipses when *D* approaches the cone of inversion whose angular radius is θ_0. For an impact parameter $\psi_0 = 0$, that is, for perfect alignment of *D* and *O*, the ellipses grow into crescents on either side of *D* and eventually join to form a ring whose diameter is $2\theta_0$ and whose thickness is approxi-