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THE VELOCITY DISPERSION OF ABELL 401

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ABSTRACT

Spectroscopic observations of 14 galaxies in Abell 401 are reported. An analysis of data for the cluster's radio-tail galaxy strongly implies the presence of in situ particle acceleration in the radio tail. The cluster velocity dispersion, 2410 km s^{-1}, agrees well with the value predicted by Solinger and Tucker from the cluster's X-ray luminosity.

Subject headings: galaxies: clusters of — radio sources: general — X-rays: sources

I. BACKGROUND

The intergalactic gas in rich clusters of galaxies has become a subject of increased interest since the discovery of extended X-ray sources and radio-tail galaxies in such clusters. It is generally agreed that the intergalactic medium is instrumental in the production of these two phenomena. However, the production mechanisms are under dispute.

It has been suggested that cluster X-ray sources may be produced by the intergalactic gas through thermal bremsstrahlung or inverse Compton scattering of the 3 K background radiation. Solinger and Tucker (1972) argue for the former emission mechanism on the basis of an apparent relationship between velocity dispersions and X-ray luminosities of clusters.

The mechanism producing radio tails in clusters of galaxies is also under dispute, a principal point being whether or not in situ acceleration is an important effect in the tails (Pacholczyk and Scott 1976; Jaffe and Perola 1973).

The competing mechanisms that have been suggested for production of cluster X-ray emission and radio tails may be tested by study of the velocity dispersions of the galaxies in the clusters involved. Data for clusters containing examples of both phenomena are particularly valuable, since physical parameters for the intracluster medium may be derived from observations of the radio-tail galaxies and applied to analyses of the X-ray sources.

We have therefore obtained spectroscopic observations of A401 ($\alpha = 02^{h}56^{m}$, $\delta = +13°23'$), a very luminous X-ray cluster which contains at least two radio sources, including a radio tail.

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II. THE OBSERVATIONS

Spectra of 14 galaxies in A401 were obtained with the 84 inch (2.1 m) telescope of Kitt Peak National Observatory and the 90 inch (2.3 m) telescope of Steward Observatory. Cassegrain spectrographs with two-stage RCA 33063 image-tube cameras were used with baked IIIa-J or IIa-O plates to obtain spectra at a dispersion of 240 Å mm^{-1}. The galaxies' spectra showed the H and K lines of calcium, and sometimes the G band, in absorption. None of the spectra contained strong emission lines.

The spectra were measured on the KPNO Grant measuring engine and reduced using the KPNO CDC 6400 computer and the reduction program of N. B. Sanwal. The resulting redshifts are listed in Table 1, and the galaxies are identified in Figure 1, where we have introduced our own numbering system.

The probable errors, estimated from multiple exposures on single galaxies, are about 150 km s^{-1}.

The redshift of galaxy 7, the radio-tail galaxy, has been confirmed by measurement of a second spectrum.

III. DISCUSSION

The cluster velocity of A401, based on the data in Table 1, is 22,380 km s^{-1}. The dispersion in radial velocities (σ_R) is 1390 km s^{-1}, implying a total cluster velocity dispersion (σ_T) of 2410 km s^{-1}. Solinger and Tucker (1972), assuming a distance of 300 Mpc for A401 and a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}, predict a velocity dispersion of 2400 km s^{-1} for this cluster on the basis of their semiempirical relation for X-ray luminosity versus velocity dispersion. Therefore, the measured velocity dispersion of A401 agrees remarkably well with this prediction, strengthening the observational support for the Solinger-Tucker relation and, therefore, the thermal bremsstrahlung model for cluster X-ray emission.

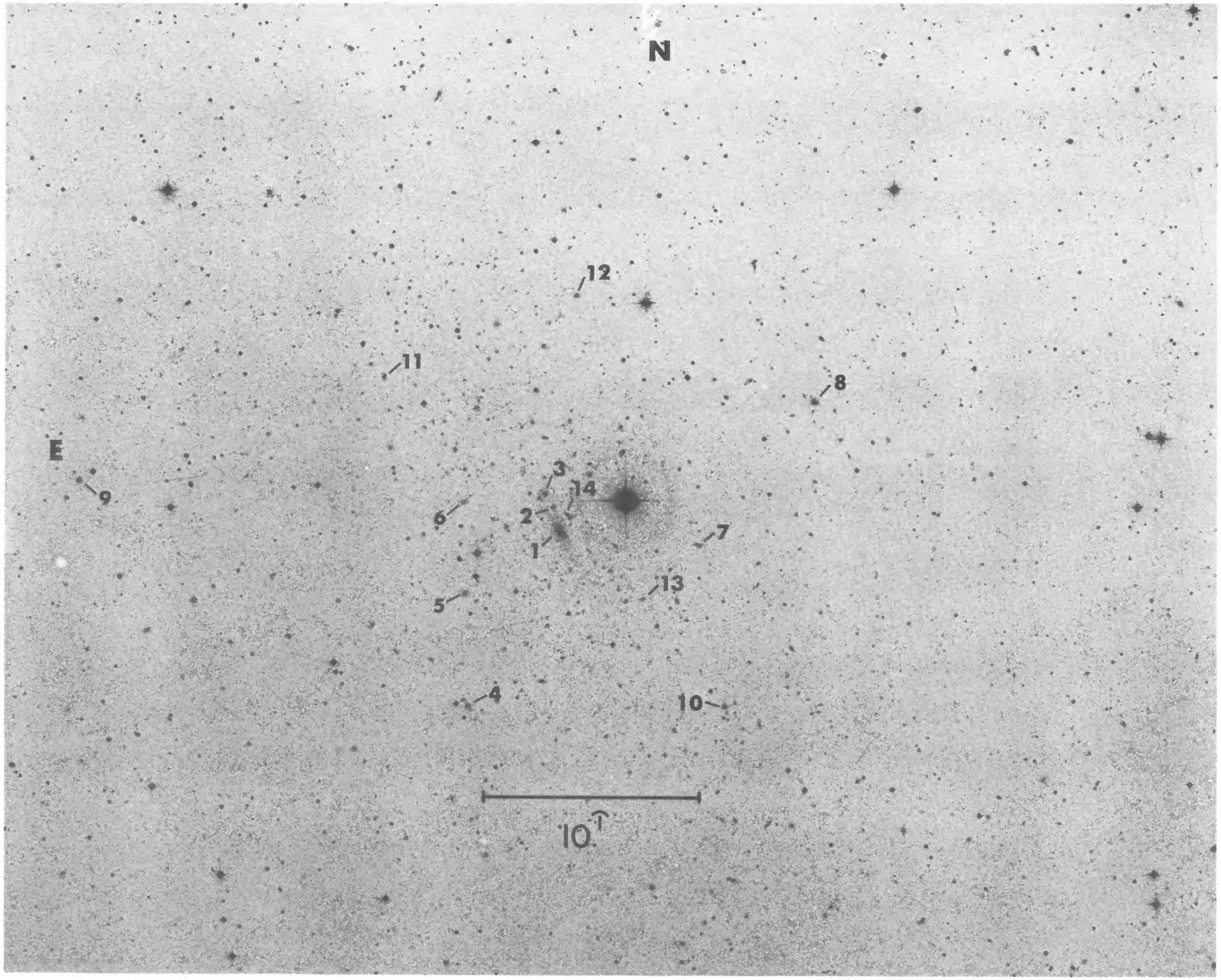

FIG. 1.—An enlargement of the red Palomar Sky Survey plate in the region of Abell 401. The galaxies we observed are identified using our numbering system.

TABLE 1

REDSHIFTS FOR A401 MEMBERS

Galaxy	α(1950)	δ(1950)	Z	V_r (km s^{-1})
1..........	02ʰ56ᵐ13ˢ	+13°23′00″	0.0745	22,340
2..........	02 56 14	+13 24 06	0.0749	22,450
3..........	02 56 16	+13 24 42	0.0804	24,090
4..........	02 56 30	+13 15 17	0.0776	23,270
5..........	02 56 31	+13 20 17	0.0737	22,100
6..........	02 56 31	+13 24 23	0.0775	23,220
7..........	02 55 47	+13 22 22	0.0650	19,500
8..........	02 55 26	+13 28 43	0.0745	22,340
9..........	02 57 42	+13 25 24	0.0756	22,660
10..........	02 55 42	+13 15 12	0.0764	22,900
11..........	02 56 45	+13 29 58	0.0675	20,240
12..........	02 56 09	+13 33 31	0.0831	24,900
13..........	02 55 57	+13 19 59	0.0729	21,840
14..........	02 56 12	+13 23 46	0.0715	21,450

In order to obtain more physical information about the intracluster medium, we now consider the radio-tail galaxy data. Galaxy 7, which is only about 6′ away from the cD member of A401, is the apparent source of the radio tail (Slingo 1974). From its proximity to the cluster's center, its radial velocity, and the necessity of a confining medium for production of the radio tail, we conclude that it is a cluster member.

This galaxy's position on the edge of the radial velocity distribution for cluster members allows us to place constraints on the projection angle of the tail with respect to the apparent plane of the sky. Assuming that the magnitude of the galaxy's velocity in the plane of the sky is less than 2.5 σ_R, the angle between the galaxy's velocity vector and our line of sight is less than $\theta = 50°$. The projected length of the radio tail at 408 MHz is 7′. Therefore, assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $\theta = 50°$, the minimum length of the radio tail is 1.17 Mpc, twice as long as that of 3C 129 (Spinrad 1975). In order to reduce the galaxy's peculiar velocity with respect to the center of the cluster, we must reduce its hypothesized tangential velocity and, therefore, *increase* the length of the radio tail.

It is the great length of the tail which allows us to draw an interesting conclusion:

The simplest assumption one can make regarding tail size is that the length of the tail, l_ν (measured at a frequency ν) is simply determined by the lifetime of the electrons, derived from synchrotron and inverse Compton losses, τ, and by the relative velocity with respect to the parent galaxy of the ejected radio components, v. The stopping time of the components in the intracluster medium is small compared to τ (this is why the tail looks like a tail), and we therefore assume v is simply equal to the galaxy's velocity relative to the cluster. Therefore,

$$l_\nu = v\tau \,. \tag{1}$$

We also know (Pacholczyk 1970)

$$\tau = \frac{1}{2.4 \times 10^{-3}(H^2 + H_{\rm eq}{}^2)E} \,, \tag{2}$$

where H is the magnetic field in the tail, $H_{\rm eq}$ is the equivalent loss field due to inverse Compton effect ($H_{\rm eq} = 3.3 \times 10^{-6}$ gauss), and E is the energy of the particles doing the emitting; and

$$\nu = 6.27 \times 10^{18} HE^2 \,, \tag{3}$$

where ν is the frequency at which the tail is observed to have length l_ν.

Having observed projected values of l_ν and v, we may solve simultaneously equations (2) and (3). We find that *even if the projection factor is unity* there are no positive solutions for H. Physically, this means that just $H_{\rm eq}$ leads to losses which make it impossible for the tail to be as long as it is observed to be without some form of compensating, in situ particle acceleration. As is clear from our earlier discussion the real length of the tail is probably considerably greater—this only strengthens our conclusion that the electrons which are emitting the observed synchrotron radiation are experiencing acceleration after they leave the parent galaxy.

If we assume a typical acceleration factor, α, from Pacholczyk and Scott (1976) such that $l_\nu = \alpha\tau v$ and $\alpha \approx 5$ (i.e., $\Delta E/E$ due to acceleration is of order 4) then $H = 6 \times 10^{-6}$ gauss, a typical value of a tail field as derived by either the Jaffe and Perola (1973) or Pacholczyk and Scott (1976) models.

This effect cannot be ascribed to remnant emission lasting several *e*-folding times longer than the synchrotron lifetime, τ. This is because physical conditions in radio-tail galaxies lead to exponential flux cutoffs beyond the critical frequency, ν, at which we measure the tail's length. Two processes will contribute to this effect. First, because the magnetic fields in radio-tail galaxies seem to be nearly uniform (Miley, Wellington, and van der Laan 1975), we are viewing electrons with a small range of pitch angles. This causes an exponential cutoff (Pacholczyk 1970). Further, this cutoff would appear even in the case of an isotropic distribution of electron pitch angles, since physical conditions in tails lead to relativistic particle streaming instability (Jaffe and Perola 1973). The relativistic electrons then randomly scatter in pitch angle, and this effect again causes an exponential flux cutoff (Christianson 1975). Since $\nu_{\text{cutoff}} \propto t^{-2}$, where t is the time since the plasma being observed was expelled, the fluxes at the beginning and the end of the tail must differ by a factor of $e^{(5)2} \sim 10^{11}$ to produce a value of $\alpha = 5$. This is clearly not the case.

IV. CONCLUSION

Abell 401 has a large X-ray luminosity and a large velocity dispersion (2410 km s^{-1}), and these two values fit very well the (L_x, velocity dispersion)-relation of Solinger and Tucker.

The simplest of assumptions about the radio tail found in A401 combined with its observed large angular extent strongly imply that in situ particle acceleration is operative in this radio tail.

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REFERENCES

Christianson, W. A. 1975, preprint.
Jaffe, V. J., and Perola, G. C. 1973, *Astr. Ap.*, **26**, 423.
Miley, G. K., Wellington, K. J., and van der Laan, H. 1975, *Astr. Ap.*, **38**, 381.
Pacholczyk, A. G. 1970, *Radio Astrophysics* (San Francisco: Freeman).
Pacholczyk, A. G., and Scott, J. S. 1976, *Ap. J.*, **203**, 313.
Slingo, A. 1974, *M.N.R.A.S.*, **168**, 307.
Solinger, A., and Tucker, W. 1972, *Ap. J.* (*Letters*), **175**, L107.
Spinrad, H. 1975, *Ap. J.* (*Letters*), **199**, L1.

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