THE ASTROPHYSICAL JOURNAL, 175:L107–L111, 1972 August 1

RELATIONSHIP BETWEEN X-RAY LUMINOSITY AND VELOCITY DISPERSION IN CLUSTERS OF GALAXIES

ALAN B. SOLINGER AND WALLACE H. TUCKER
American Science and Engineering, Cambridge, Massachusetts 02139
Received 1972 April 10; revised 1972 May 25

ABSTRACT

The connection between the X-ray luminosity L_X and the dynamics of clusters of galaxies is considered. L_X is found to be strongly correlated with the velocity dispersion ΔV. The observed relationship can be explained most simply within the framework of a thermal-bremsstrahlung model with the X-ray luminous mass being a fraction of the cluster binding mass. This implies that the clusters are or were gravitationally bound. The X-ray intensities or velocity dispersions are predicted for several clusters.

I. INTRODUCTION

There are two outstanding questions associated with the energetics of clusters of galaxies. First, these clusters are in general powerful X-ray sources with luminosities in the 2–10 keV band $L_X \sim 10^{43}$–10^{44} ergs s^{-1} (Gursky *et al.* 1972). What mechanism produces such X-ray power? Second, if the clusters are gravitationally bound, the velocity and spatial distributions of the galaxies indicate masses on the order of 10–100 times that observed in the galaxies themselves (Limber 1961; Rood, Rothman, and Turnrose 1971; Karachentsev 1966). Is this mass actually present? And if so, in what form? The purpose of this *Letter* is to consider the relationship between these questions (see also Turnrose and Rood 1970; Noerdlinger 1971; Felten *et al.* 1966 for earlier discussions along this line).

II. CLUSTER DYNAMICS AND X-RADIATION

The first indication of a connection between X-ray luminosity L_X and cluster dynamics is that L_X appears to be strongly dependent on the *richness* criterion (Abell 1958). Of the 111 nearby ($D \lesssim 300$ Mpc) Abell clusters (Sastry and Rood 1971), there are 13 of richness 2. Five of these are identified with *Uhuru* X-ray sources, and six of the eight remaining would be only marginally detectable in any case if they were as powerful as Coma (Gursky *et al.* 1972). None of the richness 0 or 1 clusters listed are observed as X-ray sources at present levels of detectability. (However, at least three other clusters for which richness is not established are X-ray sources.) The richness criterion is at best a rather loose and arbitrary classification scheme, and unsuitable for quantitative use. However, the richness of a cluster is clearly related to the space density of galaxies within it, which in turn is related to the gravitational field therein. Since the gravitational field determines the velocity dispersion ΔV of the cluster galaxies if the cluster is bound or was bound at some previous epoch, we have investigated the possibility of a correlation between L_X and ΔV.

In table 1 we list, for several clusters, the observed 2–10 keV X-ray flux, or upper limits, the distance to the clusters, the 2–10 keV X-ray luminosity (L_X), and the velocity dispersions ΔV. The clusters listed are all those for which ΔV and L_X or an upper limit to L_X is known. The sources for the data listed are given in the footnotes to table 1. Using these data we plot, in figure 1, log L_X versus log ΔV. The actual data points show a strong dependence of L_X on ΔV, and all of the upper limits are consistent with this ordering.

TABLE 1

PARAMETERS OF GALAXY CLUSTERS

Cluster	$10^{11}F_x$ (ergs cm^{-2} s^{-1}) (1)	D (Mpc) (2)	$10^{43}L_x$ (ergs s^{-1}) (3)	ΔV (km s^{-1}) (4)
Coma	21*	91	20	1800†
Perseus	68*	73	40	2400‡
Virgo	37*	15	1	1050§
Centaurus	10*	45‖	2.5	1200‖
A2199	< 6#	110**	< 9	1450§
Hercules (A2151)	< 2#	100**	< 2	1100§
A194	< 2#	110**	< 0.3	750§
UMa 1 (A1377)	< 2#	230**	<12	640§
A2065	< 2#	330**	<30	2100§
A1318	< 6#	230**	<40	700§
Canes Venatici	< 2#	6††	< 0.09	240§
A2256	5.4*	280**	50	...
A401	5.1*	300**	60	...
3C129	10*	80**	8	...
A1367	6.1*	85**	5	...

NOTE.—H_0 = 75 km s^{-1} Mpc^{-1} throughout. ΔV is corrected for projection. The prefix "A" refers to Abell (1958) clusters.

* Gursky *et al.* (1972).

† Rood *et al.* (1972).

‡ Chincarini and Rood (1971).

§ Turnrose and Rood (1970).

‖ Computed from the velocities of NGC 4696, 4706, and 4709 as given by de Vaucouleurs (1964).

Gursky and Murray (1972).

** Obtained from the redshift-magnitude relation given by Abell (1958).

†† Van den Bergh (1960).

III. DISCUSSION

In our opinion the observed strong dependence of L_X on ΔV is evidence in favor of a thermal-bremsstrahlung model for the X-ray emission from clusters of galaxies. In the inverse Compton model, the X-ray emission is produced by scattering of the 3° K background radiation by relativistic electrons, and

$$L_X \propto N_{\rm rel}\gamma^2 w_B \,, \tag{1}$$

where γ is the average energy of these electrons, and w_B is the energy density of the background radiation. To explain the X-ray emission from Coma, one needs about 10^{65} electrons with $\gamma \sim 10^3$ corresponding to an energy content $\sim 10^{62}$ ergs; their lifetime against radiation losses is $\sim 10^9$ years. The comparatively brief lifetime of the electrons and the fact that the X-ray sources are centered on active galaxies (Kellogg *et al.* 1972; Forman *et al.* 1972) suggest that in this model the electrons in each source are provided by a single active galaxy and produce the X-ray emission more or less independently of the properties of the cluster, in which case no dependence at all on ΔV is expected. Some dependence might be introduced through the fact that the electrons must be confined within the source volume; magnetic confinement is impossible since the magnetic fields required would produce an excessive amount of synchrotron radio emission. It is difficult to see how confinement by gaseous matter would introduce more than a weak [$\propto (\Delta V)^2$] dependence.

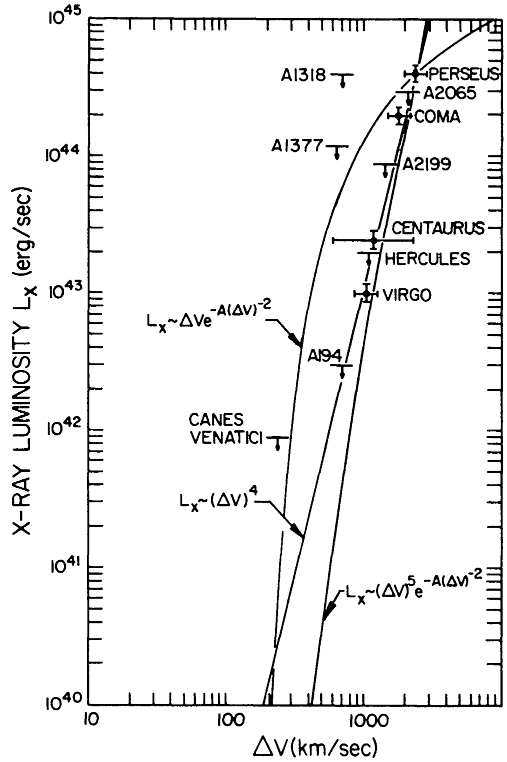

FIG. 1.—Log of X-ray luminosity (L_X) versus log velocity dispersion for clusters of galaxies. Sources are as noted in table 1. Errors in ΔV have been taken as ± 15 percent except for the dense cluster in Centaurus, for which we estimate the error at a factor of 2. The X-ray luminosities are assumed to have 10 percent error bars. The curves are $L_X = L_p(\Delta V_p)^{-4}(\Delta V)^4$, which represents heating by active galaxies, and $L_X = L_p(\Delta V/\Delta V_p)^5 \exp\{-A[(\Delta V)^{-2} - (\Delta V_p)^{-2}]\}$, which represents kinematic heating, and where $L_p = 4 \times 10^{44}$ ergs s^{-1} is the luminosity of Perseus, $\Delta V_p = 2400$ km s^{-1} is Perseus' velocity dispersion, and $A = 0.376 \times 10^6$ km^2 s^{-2}. The curve $L_X = L_p(\Delta V/\Delta V_p) \exp\{-A[(\Delta V)^{-2} - (\Delta V_p)^{-2}]\}$, which represents kinematic heating of a medium not related to the binding mass in clusters, is also plotted.

On the other hand, in a thermal-bremsstrahlung model, the luminosity above a photon energy E is

$$L_X \propto (M_X^2/V_X)T^{1/2} \exp(-E/kT)\,, \tag{2}$$

where M_X, V_X, and T are the mass, volume, and temperature of the X-ray emitting plasma. The mass M_X derived from the X-ray observations is in general larger than a galactic mass, so it must be associated with the properties of the cluster rather than individual galaxies; and since L_X depends on the square of M_X, a strong dependence of L_X on ΔV is expected. This will be true even if the mass is heated by a single active galaxy, since it is intracluster matter that is radiating the X-rays.

In order to study the implications of the observations for thermal-bremsstrahlung models in a little more detail, we isolate what we expect to be the strongest ΔV dependence by writing

$$M_X = \alpha M_{vt} \propto R(\Delta V)^2\,, \tag{3}$$

where M_{vt} is the virial-theorem mass required to bind the cluster, and R is the harmonic mean intergalactic distance. The quantity α may be a function of ΔV and other parameters describing the X-ray source. We expect it to be a weak function of ΔV. The dependence of T on ΔV is related to the heating mechanism assumed. For example, galactic wakes (Ruderman and Spiegel 1971) or cluster accretion (Gott and Gunn 1971) imply $T \propto (\Delta V)^2$. On the other hand, it may be that T is independent of the cluster kinematics and depends instead on the rate of energy input by active galaxies. These two possibilities, together with equations (2) and (3), yield

$$L_X \propto (\alpha^2 R^2/V_X)(\Delta V)^5 \exp[-A/(\Delta V)^2], \tag{4}$$

corresponding to $T \propto (\Delta V)^2$, or

$$L_X \propto (\alpha^2 R^2/V_X)(\Delta V)^4, \tag{5}$$

corresponding to T independent of ΔV. In equation (4), A is a constant that depends on the details of the model. For $E > 2$ keV and ΔV in units of km s^{-1}, A is between 10^5 and 10^6. In figure 1 we have plotted curves corresponding to equations (4) and (5) with the factor $(\alpha^2 R^2/V_X)$ assumed to be independent of ΔV and $A = 4 \times 10^5$. Both these curves approximate the data well, so we cannot determine the dependence of T on ΔV from the present observations. However, the good fit does suggest that the factor $(\alpha^2 R^2/V_X)$ is approximately a constant from one cluster to another, a fact which should provide a clue to understanding the processes involved in producing the X-ray sources. Also shown in figure 1 is the curve $L_X \propto \Delta V \exp[-A/(\Delta V)^2]$, corresponding to the case where the only dependence on ΔV is through $T \propto (\Delta V)^2$. This curve illustrates that this assumption is untenable; an additional dependence on ΔV must be introduced, and the most plausible way to do this is through M_X.

Thus velocity dispersions in galaxy clusters appear to relate to the X-ray luminous mass, which is related to the virial-theorem mass. This indicates that the clusters are or were at some past epoch gravitationally bound since, if the clusters were never bound, the velocity dispersions would not necessarily relate to the gravitational potential, and thus, the mass. If the clusters are presently bound and $M_X < M_{vt}$, then either there must exist large temperature gradients in the intracluster plasma, or much of the mass must be subluminous.

Based on the correlation, expected X-ray fluxes of about 10^{-11} ergs cm^{-2} s^{-1}, at about

TABLE 2

PREDICTED X-RAY FLUXES AND VELOCITY DISPERSIONS

Cluster	Prediction: Model A*	Prediction: Model K†
	$F_X(10^{-11}$ ergs cm^{-2} $s^{-1})$	
Canes Venatici	1	0.001
A1377	0.03	0.003
A1318	0.05	0.007
A194	0.3	0.05
Hercules	1.6	0.6
A2199	4	2
A2065	2	2
	ΔV(km s^{-1})	
A2256	2500	2500
A401	2600	2600
A1367	1400	1400
3C129	1600	1600

* Active galaxy heating: $L_X \propto (\Delta V)^4$.

† Kinematic heating: $L_X \propto (\Delta V)^5 \exp[-A(\Delta V)^{-2}]$.

the level of sensitivity of the *Uhuru* satellite are predicted for Abell 2199, Hercules (A2151), and A2065. Canes Venatici should be detectable at this level only if $L_X \propto (\Delta V)^4$; it would be a factor 10^{-3} weaker if $L_X \propto (\Delta V)^5 \exp[-A(\Delta V)^{-2}]$. This is a key measurement, therefore, in determining the heating process of the intracluster plasma. We further predict fluxes of about 0.3 for A194, 0.03 for 1377, and 0.05 for A1318 (units of 10^{-11} ergs cm^{-2} s^{-1}) if $L_X \propto (\Delta V)^4$ holds; about a factor of 10 lower fluxes are expected otherwise. We also predict these velocity dispersions for clusters which are X-ray sources: A2256 and A401, $1400\sqrt{3}$ km s^{-1}; 3C 129 and A1367, $870\sqrt{3}$ km s^{-1} ($\sqrt{3}$ is the projection correction). These predictions are summarized in table 2.

If the Canes Venatici cluster is detectable, and $L_X \propto (\Delta V)^4$, then the interpretation is clear: the heating of the intracluster medium is dominated by energy input by active galaxies. Evidence for this may already exist in the fact that the X-ray sources in Perseus, Coma, and Virgo are centered on active galaxies (Kellogg *et al.* 1972; Forman *et al.* 1972).

We thank G. Blumenthal, H. Gursky, E. Kellogg, and S. Murray for helpful discussion. This work was supported by NASA contract NAS5-11422.

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