21

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Clusters of galaxies

Clusters and groups of galaxies are now recognized to be fundamental constituents of the Universe. According to modern theory, most of the material in the Universe that has collapsed into coherent structures lies in groups of galaxies, while clusters are the only entities in the Universe that should be representative of the Universe as a whole. Thus the study of groups and clusters of galaxies is of tremendous importance. One of the most surprising distinguishing characteristics of these, the largest and most massive objects in the Universe, is that they are filled with hot X-ray-emitting gas whose mass exceeds (often by factors of 3–7) the mass of the galaxies in the groups and clusters. This gas is enriched in heavy elements (e.g., oxygen and iron) and is thus the repository of most of the metals in the Universe.

Clusters are also exceedingly sensitive tracers of the cosmological parameters of the Universe (such as its mass density Ω_m, its age H_0^{-1}, and the cosmological constant Λ) and the nature of the primordial spectrum of density fluctuations. Detailed studies of clusters and their evolution as well as their baryonic content are among the most robust estimators of the cosmological parameters (Bahcall *et al.* 1999) and at present are one of the strongest arguments for a low-Ω universe. X-ray surveys, at present, are capable of detecting clusters in a uniform robust way to redshifts >1.2 and thus provide the fundamental material for the study of cluster evolution and its cosmological impact.

Cluster mergers are thought to be the prime mechanism of massive cluster formation in a hierarchical universe (White and Frenk 1991) and represent the most energetic events in the Universe since the big bang. These mergers with infall velocities of ~2000 km s^{-1} and total masses of $10^{15}\,M_\odot$ have a kinetic energy of 10^{65} erg. The shocks and structures generated in the merger have an important influence on cluster shape, luminosity and evolution and may generate large fluxes of relativistic particles. These mergers are best studied with X-ray imaging and spectroscopy studies of the temperature, abundances and gas density, which can reveal the entropy and pressure in these systems. X-ray imaging is also required to distinguish between true mergers and the projections that one expects in a hierarchical universe (Henriksen and Markevitch 1996).

Numerical studies of large-scale structure formation show that groups are the tracers of the cosmic web, being the connection of galaxies to clusters in a hierarchical merger "tree". Thus detailed surveys of groups will provide the best measure of the nature and form of large-scale structure, which in turn will provide detailed cosmological information.

Because detailed measurements of the mass, metallicity, evolution, number density, and structure of groups and clusters of galaxies are best performed with X-ray data, X-ray astronomy has become central to the study of clusters. At present, X-ray data can yield the cluster mass, structure, and iron abundances out to redshifts of ~0.8 (Donahue *et al.* 1999), measuring the abundances and distribution of other elements at $z \sim 0.1$, finding clusters at $z \sim 1.24$ (Rosati *et al.* 1999), and determining the nature and form of cluster number and mass evolution (Henry 2000) to $z > 0.5$. Because groups are much less luminous, their study so far has been limited to the local volume of space ($z < 0.05$). Since they are extremely numerous there is hope that detailed X-ray surveys optimized for the study of

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groups will be able to map the cosmic web seen in detailed numerical simulations (Cen and Ostriker 1999).

The hot gas in the cluster potential well will scatter the microwave background and generate a signal whose strength depends on the path integral of the pressure in the cluster but is independent of distance (Sunyaev and Zel'dovich 1981). The ratio of the X-ray properties to the microwave properties is distance dependent, and provides a direct physical means of determining the angular distance to the objects and thus measuring the Hubble constant and Λ. (Frequently the Hubble constant is given in units of h, which means that it is normalized to a value of 100.) The Sunyaev–Zel'dovich effect provides an independent estimate of the cluster gas mass, which has confirmed the X-ray estimates and reinforces the large baryonic ratios in clusters.

Knowledge of the nature of the galaxies in clusters and their evolution with cosmic time has been vastly enhanced by the imaging capabilities of the Hubble Space Telescope (HST). The detailed Hubble images from the UV to the near-IR have enabled the age dating of elliptical galaxies, the most dominant population of cluster galaxies.

The HST optical data, when combined with the X-ray measurements of cluster evolution, indicates that clusters are very old, even the most massive systems having formation epochs at $z > 1$, and most of the stars in the galaxies forming at $z > 2$. This is contrary to the strong predictions of a $\Omega = 1$ closed universe (Turner 1999). The great age of the stars in cluster galaxies also indicates that most of the metals, which are found in the cluster gas, were formed at high z.

The exquisite Hubble images have also enabled the robust measurement of gravitational lensing of background galaxies by the foreground cluster. While the lenses were discovered from ground-based imaging, one requires the HST images to obtain accurate cluster mass profiles. These data can even place constraints on the fine-grain distribution of dark matter in clusters. In addition to providing measurements of the dark matter, lensing amplifies the light from the lensed galaxies, allowing detailed measurements to be made of the properties of high-redshift galaxies (Steidel *et al*. 1999).

Detailed numerical simulations of cluster formation and evolution which include the effects of dark matter and gas have reached quite high levels of sophistication (Eke *et al*. 1998). These calculations indicate that the gas is almost in hydrostatic equilibrium and that the clusters should follow a set of scaling laws. One of the most important of these laws is the relation between gas temperature and the total mass of the cluster, including gas, galaxies, and dark matter. Theory indicates that the total mass should scale as the X-ray temperature to the power 1.5 and that for massive systems the X-ray temperature is an accurate estimate of the cluster mass.

The 0.2–15 keV X-ray emission from most clusters of galaxies is dominated by thermal bremsstrahlung and line radiation from a collisionally dominated plasma with about a third of solar abundances (see Sarazin 1988 for a review). While there may be significant contributions at both lower and higher energies from synchrotron or inverse Compton radiation from relativistic particles (Sarazin 1999), the bulk of the radiated energy and the total energy in the cluster is due to thermal particles. The observed range of temperatures for clusters and groups is 0.2–15 keV, and the luminosities range from 10^{42} to $3 \times 10^{45}\,\mathrm{erg\,s^{-1}}$ (Mushotzky and Scharf 1997). There is a strong correlation between cluster luminosity and temperature (Mushotzky 1984). The strongest emission line complex from a plasma of $kT > 3$ keV is the He-like 6.67 triplet from Fe XXV, and the first studies of cluster abundances were only able to measure the flux from that line complex. In more modern work, with the ASCA (Advanced Satellite for Cosmology and Astrophysics) and BeppoSax satellites, the emission from the more abundant elements heavier than oxygen has been measured. At the lower temperatures representative of "poor" clusters and groups the spectrum is line dominated, much of the flux being emitted by a veritable sea of Fe L lines.

There is very little variance in cluster metal abundances for massive systems with $kT > 3$ keV, but at lower temperatures (and masses) there appears to be a wide range of abundances and a variation in the range of Si to Fe abundances, indicative of a different formation of heavy elements as a function of cluster mass. These lower-mass systems also have more entropy per unit particle than is indicated by the numerical simulations, indicating, perhaps, that there has been additional energy injected into the intergalactic medium (IGM) other than by gravity. The amount of energy implied is rather large and should have significant effects on group and cluster formation.

Detailed analysis of the cluster temperature and gas density provide, via the equation of hydrostatic equilibrium, robust estimates of the total cluster mass and gas mass. It became clear at the beginning of the 1990s (White *et al*. 1993) that the dark matter in clusters accounted for "only" ~80% of the total mass. However, in the closed $\Omega = 1$ Universe popular at the time, dark matter should account for ~94% of the total mass. Since clusters are thought to be fairly representative samples of the Universe, this was a strong indication that either the theory of cluster formation had a serious error or that $\Omega \ll 1$, with a best estimate for Ω being 0.3, for example the ratio of the baryons in the clusters to the dark matter compared to the cosmic ratio.

In the centers of a large fraction of luminous clusters the X-ray-emitting gas has a cooling time, in the absence of any known sources of heat, which is considerably less than the Hubble time, so one anticipates that the gas should be cooling (Fabian 1994). In the most spectacular examples of this phenomenon the gas should be cooling at a rate of $>1000\ M_{\odot}\ \mathrm{yr}^{-1}$. X-ray spatial and spectral measurements provide striking confirmation of this idea, but the eventual repository of the cooled material has proven to be elusive. The luminous galaxies that reside at the centers of cooling flows have a wide variety of unique properties in the UV, optical, IR, and radio bands which indicate that the cooling flow phenomenon has important consequences not only for the hot gas but also for galaxy formation and evolution. If the final repository of the cooling gas is stars, as it clearly is for some of the material (O'Connell and McNamara 1988), then this process could be a major factor in massive galaxy formation.

The field has undergone an enormous change, driven primarily by a vast improvement in technical capability since the first discovery of X-ray cluster emission during a rocket flight in 1968 (Friedman and Byram 1967). The development of spacecraft allowed the first all-sky surveys with Uhuru in 1971 and Ariel 5 in 1975 (Gursky *et al*. 1971, Villa 1976), the development of low-background proportional counters resulted in the first X-ray spectra with Ariel 5 (Mitchell *et al*. 1976) and OSO 8 (Serlemitsos *et al*. 1977); and the development of imaging X-ray optics made possible the first X-ray images, with the Einstein Observatory (Jones *et al*. 1979), and the large number of images and spectra with Rosat, ASCA, and BeppoSAX in the 1990s. The development of X-ray photon-counting CCDs combined with high-throughput thin-foil optics led to the first high-quality spectra of numerous clusters with ASCA. The tremendous improvement in sensitivity, spectral resolution, and spatial resolution allowed by the spectacular increase in angular resolution made possible by the Chandra mirror and the technology breakthrough resulting in the very large collecting area of XMM-Newton will push X-ray cluster studies to new levels of sophistication and detail in the first decade of the new century. The spectacular improvement in spectral resolution that would have been brought about by the calorimeter on Astro-E will have to await a future flight of this technology, due to the failure of Astro-E to reach orbit.

To go beyond these three new missions will require even larger collecting areas and better spectral resolution, as will be possible with the Constellation-X mission under study in the USA. While the progress in the 1990s was truly spectacular, we anticipate even more rapid progress in the next decade.

HISTORICAL CONTEXT

(See Bahcall (1977) for an early review.) Clusters of galaxies are the largest virialized structures in the Universe, with masses of 10^{13}–$3\times10^{15}M_\odot$ and sizes of 1–3 Mpc. They were discovered rather early in the history of modern astronomy – by Herschel (as noted by Lundmark 1927) – but it was not until the 1930s (Zwicky 1937, Smith 1936) that they were recognized as very large conglomerations of galaxies at great distances. The first dynamical analysis of clusters showed that there must exist much more gravitational material than was indicated by the stellar content of the galaxies in the cluster. This was probably the first discovery of the preponderance of dark matter in the Universe. However, the field did not advance much until the early 1960s, for what seems, in retrospect, to have been the simple reason that astronomers did not want to accept that most of the material in the Universe was dark.

With ever larger ground-based telescopes, cluster research developed along the lines of measuring the numbers, sizes, luminosity, and spatial and velocity distribution of the galaxies. The development of large catalogs of clusters (Abell 1958, Zwicky and Herzog 1963) based on eye estimates of the number of galaxies per unit solid angle was a major milestone in the field. The relatively strict criteria for the Abell catalog proved to be a good guide to the physical reality of the objects, and it is amazing that 40 years later we are still using this catalog. Extensive optical follow-up studies of objects in these catalogs was more time-consuming, and it was not until the early 1970s (Rood 1974) that the first large samples of estimated cluster mass from measurement of the velocity distribution of the galaxies via the use of the virial theorem were obtained.

By the early 1970s it became clear (see the pioneering paper of Rood *et al*. (1972), and the detailed study of the Coma Cluster by Kent and Gunn (1982)) that clusters of galaxies were dominated by dark matter, with galaxies representing less than 5% of the total mass, and that there were definitive patterns in their galaxy content (Dressler 1980). Thus the issue of the "missing mass" or "dark matter" became the central theme of cluster research.

The nomenclature of the field was partially defined by Abell's survey of the northern sky for clusters based on a visual search of the Palomar Observatory Sky Survey plates. He defined a set of "richnesses" and distance classes based on the apparent magnitudes of the galaxies and the number of galaxies inside a fixed "metric" radius. Abell used strict criteria to define the physical reality of a cluster.

"Rich" clusters (i.e., those with many galaxies inside a fixed metric (Abell) radius) had a preponderance of "early" type (elliptical and S0) galaxies, while "poorer" clusters had a larger fraction of spiral galaxies. It was clear that many clusters had a rather unusual central galaxy, a cD, or centrally dominant galaxy (Morgan and Osterbrock 1969) which is very seldom, if ever, found outside clusters. There was also an unusual type of radio source found primarily in clusters, a so-called WAT, or wide-angle tailed source (Owen and Rudnick 1976). There were the first indications of cluster evolution (Butcher and Oemler 1978) in which distant clusters at $z \sim 0.2$ tend to have "bluer" galaxies than low-redshift clusters (to an optical astronomer elliptical galaxies have rather "red" colors while spirals tend to be bluer), but the morphology of these galaxies was unknown.

However, the fundamental realization (Binney and Strimpel 1978, Heisler *et al*. 1985) that the mass of the cluster could not be precisely determined from galaxy position and velocity distributions severely hampered further progress. The mass of clusters was parametrized by the so-called mass-to-light ratio (in solar units, so the Sun has a value of 1). This is the ratio of the two quantities that can be well estimated by optical data: the total amount of light in the system and a dynamical estimator of the mass (most often the virial estimator). For most clusters the values were ~$400\,h^{-1}$ (the mass to light ratio depends on the distance to the cluster since the total light is proportional to flux $\times$ distance^2, while the virial mass estimator is proportional to velocity dispersion $\times$ cluster size). There were also technical difficulties with measuring the effective cluster size and the total amount of light, and with determining the velocity dispersion in the presence of sub-structure in the cluster and foreground and background contamination (see Oegerle *et al*. (1989) for a status report).

Since the mass-to-light ratio of "normal" galaxies is in the range of 2–12, this large value for clusters indicated the presence of large amounts of dark matter. However, mass-to-light ratio is not a basic astrophysical quantity since it depends on the age, initial mass function, dust content, and metallicity of a stellar system as well as on the optical color system in which it is obtained. Sensible values from 1 to 20 can be obtained without the need for dark matter. Thus, while these data strongly indicated the presence of dark, non-baryonic material, its abundance and nature could not be strongly constrained.

One of the most surprising discoveries of the space age has been that most of the baryonic material in clusters is in the form of hot X-ray-emitting gas which is enriched in heavy elements to about a third of solar abundances. This discovery came about in stages (see the next section), and it is now realized that X-ray emission from clusters is a dominant process and that, in some sense, clusters of galaxies are X-ray objects. This discovery was essentially entirely unpredicted and has led to fundamental change in our understanding of the Universe. It is rather surprising to realize not only that most of the material in the Universe is dark and non-baryonic, but that most of the baryons in the Universe do not shine in optical light. The anthropomorphic picture that the Universe is best studied with the light visible to our own eyes is not only seriously in error, it drives science in the wrong directions.

Since the discovery of X-ray emission from clusters, the nature of the optical data has changed radically. The ability of multi-fiber spectrographs to obtain velocities for hundreds of galaxies in the cluster and of CCD imagers to obtain accurate multi-color photometry for many hundreds has vastly improved the quality of the data. At present it is the combination of X-ray, optical, and even radio and IR data that yields the best constraints on the physical parameters of clusters.

The ability of modern instrumentation to observe clusters at all mass scales over a wide range of redshifts has made them one of the prime areas of extragalactic research. Their use as cosmological probes, as large samples of galaxies, and even as "fair samples" of the Universe has made the study of clusters a rather exciting area of research. From a theoretical point of view the rather "simple" physics involved in their formation and evolution makes their properties amenable to "first principles" calculation and allows a direct comparison of theory and observation. A quick look at the main journals shows hundreds of papers a year being published in this area, and the rate of increase is rapid.

THEORETICAL CONTEXT

Physical models of clusters

Modern theories of cosmology and large-scale structure are built on the assumption that cold dark matter (CDM) is the main form of dark matter in the Universe and that, based on inflation, there is an initial power density spectrum of fluctuations. This theory has a set of "free" parameters – the Hubble constant H_0, the mass density in gravitating material Ω_m, the fraction of the closure density in cold dark matter particles, the value of the cosmological constant Λ, the normalization of the power spectrum σ_8, the baryonic fraction (the fraction of the closure density in baryons) Ω_b, and the amount of "hot" dark matter. While this is rather a large set of free parameters, most of them are fairly well determined by observation. In this CDM theory, structure forms in a "bottom-up" scenario in which small masses form first and larger structures such as clusters form later. However, this is a vast oversimplification, and a wide range of mass scales collapse at a wide range of redshifts. For a $\Omega_m = 1$, $\Lambda = 0$ universe (the paradigm before the late 1990s), clusters form at rather low redshifts, and Gott and Gunn (1972) referred to the present as "the epoch of cluster formation."

Because clusters are the largest virialized systems in the Universe they are at the tail end of the distribution of fluctuations, so-called 3σ fluctuations. Their formation and evolution is thus very sensitive to the cosmological parameters (see Bahcall *et al*. 1999 for a recent review). Most cosmological models, in fact, are normalized by the COBE spectrum of fluctuations and the abundance of massive clusters – so-called cluster normalized models.

Before the late 1970s theoretical work focused on mechanisms for "relaxation" (so-called violent relaxation

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