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Can Mergers Explain Cooling Flows?

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Sparks, Macchetto & Golombek (1989) proposed that capture of the cold interstellar material of a companion galaxy, or accretion of a small gas-rich dwarf, by a hot X-ray emitting corona could explain the observations traditionally interpreted as a cooling flow. In this picture, the heat flow from hot coronal gas to cold "merged" gas locally cools the X-ray gas and enhances its luminosity, while providing the energy which is radiated as optical emission lines and infrared radiation from the gas and dust of the cold phase. The merger event forces the inner boundary temperature and avoids difficulties of fine tuning with self-contained thermal conduction models. We will examine this idea in the light of current high quality data from optical and X-ray facilities and assess whether it remains a viable option.

1. **Introduction**

The "warm" ionized plasma with temperatures around 10^4K found in cooling flow galaxies represents an intriguing component of the interstellar medium. This component may hold the key to a general understanding of the physical processes at work in these environments.

In addition to massive hot X-ray emitting coronal gas with temperatures 10^7 K, cooling flows also typically have extended low-excitation warm gas at 10^4 K that emits by line emission, seen most readily in optical wavelengths through strong emission lines of Hα and [NII]. Cooling flows have been found to contain much cooler gas in some cases, and, at the other extreme, highly relativistic energetic plasmas associated with active nuclei (AGN), jets and radio sources. Understanding the interrelationships between these diverse plasmas represents an exciting challenge that may lead to a description of the physics of the interstellar medium in these remarkable environments.

By focusing on the warm plasma, and trying to understand what its origin is, what the excitation mechanism is, and what the ultimate fate of such gas may be, we probe important questions relating to the evolutionary processes in the interstellar medium, the physics of the interstellar medium, and the powering of active nuclei and feedback into the interstellar medium, as well as the important interrelationships between all of these.

2. **Optical Observations of Cooling Flows**

2.1. *Early Observations and Implications*

When optical filaments were discovered in cooling flows it was thought to be a major success for the theory (Hu, Cowie & Wang 1985; Heckman et al. 1989). The filaments were believed to have their origin in the thermal instability of the coronal gas, which itself was responsible for the entire "cooling flow" (Fabian 1994). Problems exist with that interpretation however, including the high luminosity of the filaments, their small spatial extent, and their dustiness since gas in the hot phase will have had its dust destroyed through sputtering. The cooling flow theory also suffers from the long standing failure to find large amounts of cold material, and most recently, the failure to detect the predicted intermediate temperature plasma by *XMM-Newton* (Molendi & Pizzolato 2001; Böhringer et al. 2002; Matsushita et al. 2002; Molendi 2002; Donahue & Voit 2003).

A straightforward alternative for the origin of the filaments is that they were accreted from elsewhere, from a gas rich spiral or dwarf galaxy. This is consistent with the optical properties of the filaments, and leads to a more unified picture with active galactic nuclei and radio galaxies, where the material responsible for re-activating the supermassive black hole is widely thought to be introduced through a stochastic merger process. In turn, this may be important to galaxy cluster physics as the energetic input from AGN may be a crucial element of the overall energy budget, needed to help balance radiative X-ray losses (Reynolds, Heinz & Begelman 2001; Churazov et al. 2001; Ruszkowski & Begelman 2002).

The alternative scenario, therefore, that the filaments represent the gaseous debris of a merger event into an ambient coronal-plasma environment will be considered here.

2.2. *Dust in Filaments*

A common property of the ionized gas in elliptical galaxies and cooling flows is that it always contains dust. This is seen through extinction, where the dust dims or obscures the light of the host galaxy across the region of the filaments. This is significant because the initial presumption was that gas condensing from the coronal phase because of thermal instability would be dust free. The lifetime of dust to sputtering by hot electrons is short compared to timescales relevant to the hot gas.

The presence of dust has also been inferred from spectroscopic observations, with line strengths indicating depletion of heavier elements onto grains (Donahue & Voit 1993), and through analysis of far-infrared fluxes (Goudfrooij & de Jong 1995). Sparks, Macchetto & Golombek (1989) showed that the dust extinction regions are spatially coincident with the line emitting gas, which was also deduced by Donahue & Voit (1993).

An important observation regarding the dust in NGC 4696 was that its wavelength dependence of extinction was found to be identical to Galactic, within the

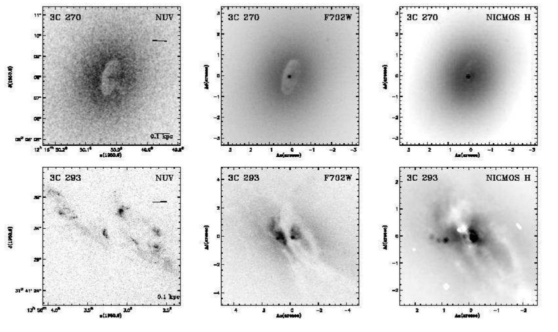

Fig. 1.— Two types of dust lanes: above, ordered disk, no star formation, processed dust, older? Below, chaotic extended dust, Galactic extinction law, some star formation, youthful? See Allen et al. (2002).

small uncertainties. This was found generally to be the case by Goudfrooij et al. (1994) for the galaxies hosting irregular or chaotic dust lanes, and it suggests that the dust in these situations has not been subjected for long to the hostile, extreme environment of the 10^7K coronal plasma. Again, sputtering by the hot electrons would destroy the dust in a way dependent on the grain size, and hence change its size distribution and wavelength dependence of extinction.

By contrast, Goudfrooij et al. (1994) and Martel et al. (2000) both found that where the dust is in a smooth, settled configuration (see Fig. 1), there are in fact departures from the standard Galactic extinction law.

While it may be that thermally unstable material from the coronal phase could form dust, we consider a more prosaic alternative which is that the dust was created elsewhere through the usual process of stellar mass-loss and condensation, and resides primarily in cold, dusty clouds in spiral galaxies and other late-type stellar systems. Such cold material may then be deposited into the hot environment of the elliptical galaxy or cooling flow through tidal stripping or mergers.

The presence of dust within the filaments is then a very natural consequence of its having arisen in a normal, cold interstellar medium environment. Similarly, the "normal" behavior in terms of the grain size distribution (from the extinction law) in the most extended, chaotic systems follows. There are other reasons to suppose that gas and dust in general are accreted from outside rather than their origin lying in internal processes. Typically, they have high angular momentum, much higher than the elliptical galaxy. The morphology of dust lanes has been modeled as an evolving warp (Quillen & Bower 1999) and sometimes there are signatures of a merger with a kinematically cold stellar component. Such signatures take the form of sharp continuum arcs or "shells" and radial tidal features, seen morphologically, and in some instances through the presence of kinematic substructure, observed spectroscopically.

Hence we infer a scenario in which chaotic dust and gas systems represent a youthful, recent infall or merger phenomenon, while more settled gas and dust disks are later stages of the same type of event (Sparks et al. 2000; Allen et al. 2002).

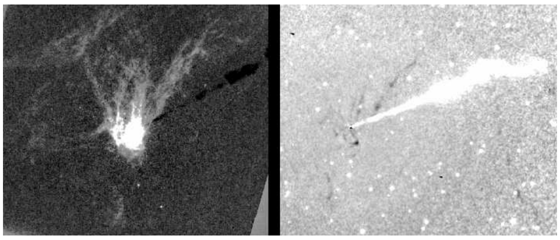

Fig. 2.— Hubble Space Telescope images of Hα + [NII] line emission (left; courtesy H. Ford) and dust obscuration (right) in the central region of M87. The images also show the famous optical synchrotron jet. The dust and gas properties were studied in detail with ground based observations by Sparks, Ford & Kinney (1993).

2.3. *Examples of Nearby Cooling Flows*

Here we look at examples of nearby cooling flows and ask whether they show other phenomena that may be attributable to mergers. Sometimes, it is tempting to infer the accretion of material from one galaxy into another, simply from the appearance of the objects. An example may be found in NGC 4105, (Sparks 1997), and also in the spectacular early images released from the Advanced Camera for Surveys (Tran et al. 2003).

A detailed study of the emission filaments and dust lane of NGC 4696, the dominant elliptical at the center of the Centaurus Cluster of galaxies, was presented by Sparks, Macchetto & Golombek (1989). The cluster itself is thought to be undergoing a merger, with a clear bimodal distribution in galaxy velocities (Lucey, Currie & Dickens 1986). Additionally, there is a faint, diffuse continuum light feature that has been modeled as the tidal disruption of a low surface brightness disk galaxy (Calcáneo-Roldán et al. 2000). Perhaps this encounter or one like it could be responsible for the origin of the gaseous material in the central region.

A fine example of a dusty emission filament system is provided by M87. Fig. 2 shows the optical line emission of M87 as seen by WFPC2 (courtesy H. Ford) next to an image showing dusty regions of obscuration. Note the wealth of features such as loops and twists that are reminiscent of plasma phenomena seen in the Solar atmosphere. Comparison of the two shows that the patches of dust coincide in many details with the regions of line emission and again the wavelength dependence of extinction is consistent with Galactic (Sparks, Ford & Kinney 1993). A diffuse fan of emission, also interpreted as tidal disruption of a small companion, has also been found in M87, (Weil, Bland-Hawthorn & Malin 1997).

An additional superb example of optical emission filaments within the galaxy at the center of the Perseus cluster, NGC 1275, was presented by Conselice, Gallagher & Wyse (2001). These filaments display an extraordinary wealth of structure, including tangential and radial filaments covering a high fraction of the face of the galaxy. As well as its spectacular emission filaments, the system hosts an amazing variety of astrophysical phenomena, including a very active nucleus, episodic star formation, dust lanes and even an infalling companion object moving towards NGC 1275 at ≈ 3000km s^{-1}. Note that even if this foreground companion is well in-front of NGC 1275, it is moving so fast that it is likely to reach the center in much less than a dynamical timescale for NGC 1275. There are shells and other fine structures in the continuum light and the star formation appears to be episodic. Conselice, Gallagher & Wyse (2001) suggest that all these features are causally connected by a recent merger and active nucleus, themselves related.

3. Interaction with the Coronal Plasma: Conduction

Hence a consistent picture emerges in which dusty, cold gas is accreted into the hostile environment of the elliptical galaxy, bringing with it the signatures of merging, and leading to the subsequent triggering of an AGN. The AGN in turn can provide energetic feedback into the interstellar medium of the elliptical galaxy.

However, there is an observational fact that may be a difficulty for this scenario, which is that the presence of optical line emission correlates well with the X-ray properties of the elliptical. This correlation has been known for a long time, and may be considered very well-established, e.g. (Hu, Cowie & Wang 1985; Heckman et al. 1989; Macchetto et al. 1996). Is this correlation consistent with a merger origin and evolution for the filaments system?

Discussion of this question leads from the origin into consideration of the excitation mechanism of the filaments. A large variety of options have been proposed including photoionization by hot stars, both young and old, photoionization by an active nucleus, recombination from a hotter phase and shocks. Here, with an eye to the correlation with X-rays, we consider another possibility, which is conduction of heat energy from the hot coronal gas into the cold merging gas.

The thermal drain from the hot plasma enhances its X-ray emission in order to retain pressure equilibrium, hence the signatures of mergers are present, while a correlation with the X-ray characteristics is induced. *The consequence however is that a fundamental transport process (and conduction may not be the only one) must operate,* the hot and cool phases communicate with one another, and the overall description of the physical processes in these environments is profoundly affected.

Discussion of heat conduction in the general context of clusters of galaxies has become fashionable, (Malyshkin 2001; Fabian et al. 2002; Voigt et al. 2002; Zakamska & Narayan 2003). In addition, there is a long history of early work in which many of the concepts were proposed, (Tucker & Rosner 1983; Rosner & Tucker 1989; Sparks, Macchetto & Golombek 1989; Sparks 1992). The conclusions of these studies are that heat conduction is not totally suppressed, that it can suppress the thermal instability alluded to above, and that in some cases the heat flow can balance the X-ray radiative losses.

For the specific application to optical emission filaments, (Sparks, Macchetto & Golombek 1989) showed that the energy flux available from saturated heat conduction was well-balanced to the energy radiated in line emission. Macchetto et al. (1996) showed that the same global energetic calculation applied generally to emission systems in elliptical galaxies. Hence the global energetics are consistent.

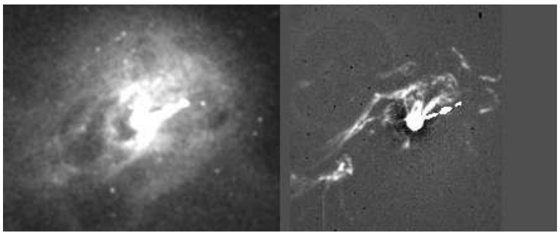

Fig. 3.— Optical Hα + [NII] filaments (left) compared to deep *Chandra* X-ray image (right; courtesy P. Coté). Note the similar features in both images despite a factor 1000 difference in temperature.

If, however, the filaments are responsible for cooling the X-ray gas, there should also be local correlations. The X-ray and optical morphologies should be similar. New *Chandra* X-ray observations allow us to test this.

Sanders & Fabian (2002) present a deep *Chandra* X-ray study of the Centaurus Cluster of galaxies. The over topology, with a swirling one-armed spiral, is similar to the optical gas and dust images of Sparks, Macchetto & Golombek (1989). The lengths scales are significantly large however, and so the detailed relationship between the two remains somewhat unclear.

Another example is provided by the X-ray tail in Abell 1795, which is morphologically very similar to the Hα morphology (Fabian et al. 2001). In this case, the X-ray and Hα images are essentially indistinguishable suggesting a close connection between the two.

Young, Wilson & Mundell (2002) showed an early *Chandra* image of M87 and noted that there are similarities between the optical line emission morphology and features in the X-ray image. Here, we present new, much deeper, data on the center of the Virgo cluster, M87. Fig. 3 shows the optical emission compared to a very deep X-ray image. Comparison of the two reveals that there is a remarkable degree of correspondence between the images, despite the factor 1000 difference in temperature. To the east, there are blobs and linear features, knots and arcs all present in both sets of data. To the North and elsewhere, small filaments and irregular patches may be seen to coincide. There are some cases of optical emission without X-ray, and vice versa, but overall, there is a high degree of correlation. The same phenomenon was shown to be present in NGC 1275 (Perseus) by Fabian et al. (2003), see elsewhere in these proceedings.

4. Conclusions

The merger/conduction combination results in a good scorecard. Global energetic balance considerations are consistent; the optical characteristics (dust, signs of mergers) are consistent and the spatial correlation between hot and warm phases is consistent.

There are significant uncertainties in the magnetic field, lifetimes of filaments, evaporation or condensation, and optical modeling of spectra which has not been carried out.

However, it is apparent that the scenario merits serious investigation and we encourage theoretical analysis of the infall of cold plasma into coronal plasma, together with observations targeted at determining whether or not mergers have occurred and at the topology of the magnetic fields in such environments.

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