The Cosmological Context of Extraplanar Gas

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Abstract. I review evidence that galaxies form from gas that falls into po-
tential wells cold, rather than from virialized gas, and that formation stops once
an atmosphere of trapped virialized gas has accumulated. Disk galaxies do not
have such atmospheres, so their formation is ongoing. During galaxy forma-
tion feedback is an efficient process, and the nuclear regions of disk galaxies
blow winds. The cold infalling gas that drives continued star formation has a
significant component of angular momentum perpendicular to that of the disk.
Extraplanar gas has to be understood in the context set by nuclear outflows and
cold skew-rotating cosmic infall.

1. Introduction

For a quarter of a century work on galaxy formation has been dominated by the
belief that when a density perturbation goes non-linear and collapses, its baryons
are shock heated to the virial temperature $T_{\text{vir}}$, so the raw material for galaxy
formation is hot gas, and galaxies form by the cooling of virial temperature
gas (Rees & Ostriker, 1977; White & Rees, 1978). Several recent developments
indicate that this picture is fundamentally flawed (Binney, 2004a). In the process
of summarizing these developments I hope to persuade you that galaxies form
from gas that is much colder than $T_{\text{vir}}$, and that galaxy formation ceases once
all its gas becomes hot. Feedback is an efficient process, and Active Galactic
Nuclei (AGN) play a crucial role by setting the upper limit to the luminosities
of galaxies. In disk galaxies a wind from the nuclear regions coexists with infall
of cold gas to the disk, and the dynamics of extraplanar must be affected by
interactions with both outflowing and infalling material.

2. Lessons from ‘cooling flows’

The deep gravitational potential wells of massive elliptical galaxies and clus-
ters of galaxies have long been known to contain major quantities of virial-
temperature gas that can be studied through its thermal X-ray emission. Un-
til recently it was conventional to suppose that this gas is passively cooling
(e.g. Fabian, 1994). To reconcile this belief with the measured radial surface-
brightness profiles of these systems, it was necessary to conjecture that the
medium was everywhere multiphase, and that throughout the sphere in which
the cooling time $t_{\text{cool}} = 3kT/2\dot{E}$ equals the Hubble time, very cold gas was
‘dropping out’. X-ray spectra from the new satellites show that in clusters of
galaxies there is much less gas at $T \lesssim \frac{1}{3}T_{\text{vir}}$ than the cooling-flow model predicts
In fact, there is no spectroscopic evidence for temperature variations on very small scales within the X-ray emitting gas – the gas appears not to be multiphase after all. There are temperature fluctuations on scales large enough to be resolved by Chandra. Downward fluctuations are associated with the filaments of cold gas that have long been a puzzle. The strong Hα emission from these objects is probably powered by embedded star formation, and smooth temperature gradients appear to connect a filament to the embedding thermal plasma (Fabian et al., 2003). Elsewhere sharp steps in $T$ are observed that extend large distances through the source (Markevitch et al., 2000). These ‘cold fronts’ are presumably contact discontinuities of the type expected in a highly turbulent fluid.

An AGN invariably sits at the centre of a ‘cooling flow’, and there is now clear evidence that jets thrown out by this object are doing significant work on the thermal plasma (e.g. Nulsen et al., 2002; Heinz et al., 2002a). The jets create regions of low or negligible thermal X-ray emission, and weak shock waves must be spreading out from these ‘cavities’. Transsonic turbulence must be generated as the underdense cavities rise and break up (Churazov et al., 2001; Quilis, Bower & Balogh, 2001; Churazov et al., 2002; Brüggen et al., 2002; Omma et al., 2004; Omma & Binney, 2004). These phenomena confirm the correctness of the general picture I developed with Gavin Tabor a decade ago (Tabor & Binney, 1993; Binney & Tabor, 1995) in which an unsteady equilibrium is set up between radiative cooling and heating through the temperature dependence of the accretion rate onto the central black hole. We argued that the dominant channel for the heating is the decay of the turbulence that is driven by jets emanating from the black hole. Although some controversy still surrounds this point (Birzan et al., 2004), the data appear to be compatible with our prediction (Binney, 2004b; Nipoti & Binney, 2004b).

What needs stressing is the implication of these findings for the White–Rees picture of galaxy formation: where we actually see trapped virial-temperature gas with a short cooling time, it isn’t cooling to form stars, but seems to be thermostated at $T \approx T_{\text{vir}}$. What reason have we to suppose that gas at $T_{\text{vir}}$ behaved differently in the past?

3. Lessons from quasars and stellar populations

It is now clear that quasars and other AGN are powered by the formation of the black holes (BHs) that are found at the centres of all sufficiently nearby, luminous galaxies. Studies of the demographics of these BHs and the luminosity functions of AGN of various types in different redshift ranges give strong indications of the role that BHs play in galaxy formation. Two findings are crucial:

- There is a tight correlation between the mass of the galactic-centre BH and the velocity dispersion of the host spheroid, which is itself correlated with the spheroid’s mass (Tremaine et al., 2002).
- The energy radiated by luminous quasars is comparable to the energy that can plausibly be extracted during BH formation. Moreover, most of this energy must have been radiated at near-Eddington luminosities (Yu & Tremaine, 2002). Consequently, the characteristic timescale on
which BHs grow is the Salpeter time $t_{\text{Salp}} \simeq 25 \text{ Myr}$, and a BH can grow from a seed mass $\lesssim 1000 \, M_\odot$ to the largest observed BH masses $\sim 10^9 \, M_\odot$ in a time $\lesssim 1 \, \text{Gyr}$ that is small compared to the Hubble time.

Comparison of the redshift evolution of the quasar density and the density of star formation then leads to the conclusion that

- The rate of black-hole formation is consistent with being proportional to the rate of overall star formation (e.g. Haiman, Ciotti, & Ostriker, 2004).

Finally, studies of early-type galaxies at low redshift (Mehlert et al., 2003) show that

- the central regions of massive spheroids are old and have enhanced abundances of the $\alpha$ elements, implying that they formed all their stars at significant redshift and on a timescale that is short compared with the timescale $\gtrsim 1 \, \text{Gyr}$ for enrichment by type Ia supernovae.

From these facts is clear that BHs and spheroids formed together during orgies of star-formation and topsy BH growth. This era of growth may have been broken into several episodes, but the elapse of time from the onset of serious star formation through its completion cannot have significantly exceeded a Gyr.

Since stars are observed to form from very cold ($T \lesssim 30 \, \text{K}$) gas, it follows that BHs fed from such cold gas also. Presumably they fed quickly at this stage because they fed off very dense cold gas. Now they are growing very much more slowly because they can eat only hot rarefied gas. Then the energy released as they grew was radiated with great efficiency by the dense surrounding gas. Now that they are surrounded by plasma too rarefied to radiate efficiently, jets carry away most of their energy output (Owen Eilek & Kassim, 2000; Di Matteo et al., 2003). In fact, it is not clear that BHs are growing at all at the present epoch, since the energy carried away by the jets may be energy stored in BH spin since those early days of topsy growth.

4. The critical mass $M_*$

We have seen that there are observational indications that spheroids formed from cold gas rather than gas at $T_{\text{vir}}$ as White & Rees (1978) assumed. Simulations of galaxy formation suggest a substantial fraction of the baryons that fall onto a protogalaxy should, in fact, arrive cold rather than at $T_{\text{vir}}$. Katz et al. (2003) used N-body/SPH simulation to determine as a function of redshift the rate of infall of gas onto a typical protogalaxy, and for each parcel of gas determined the highest temperature $T_{\text{max}}$ achieved. They found that the rate of infall declined with $z$, slowly from $z = 3$ to $z = 2$, and then quite rapidly. At all redshifts $T_{\text{max}}$ ranged from $10^4$ K to $10^7$ K. At $z = 3$ the distribution of $T_{\text{max}}$ was strongly bimodal with about equal quantities arriving either side of $2 \times 10^5$ K. At the present epoch the distribution was fairly flat, with a continuous transition at intermediate $z$.

Birnboim & Dekel (2003) studied the infall of gas onto a galaxy-sized overdensity semi-analytically. They showed that post-shock cooling is so efficient
that the accretion shock does not break away from the centre of the system in systems that contain $\lesssim 3 \times 10^{10} \, M_\odot$ of baryons. This mass coincides remarkably accurately with the characteristic baryonic mass $M_*$ that emerges from the SDSS data for relatively nearby galaxies [Kauflmann et al., 2003]: below $M_*$ surface brightness increases with $M$, the galaxies are relatively young and not very centrally concentrated, while above this mass surface brightness is independent of $M$, and galaxies are old and centrally concentrated.

It has been recognized for a very long time (Larson, 1974; Dekel & Silk, 1986) that heating by core-collapse supernovae picks out a mass scale that is similar to $M_*$: for a given IMF, supernovae inject a well defined energy per unit mass. The temperature $T_{\text{SN}}$ to which the ISM can be heated by this energy depends on the efficiency of radiative cooling and on how uniformly the energy is distributed. A reasonable estimate is obtained by neglecting radiation losses (which leads to $T_{\text{SN}}$ being overestimated) and assuming that the energy is shared by all the surviving gas (which causes $T_{\text{SN}}$ to be underestimated). With these assumptions, $T_{\text{SN}} \sim 1$ keV, $T_{\text{SN}} = T_{\text{vir}}$ for $M \sim M_*$. Hence it is unclear whether $M_*$ has been imprinted on the observational by the physics of gravitational heating, or by SN heating. However, the following line of argument suggests that SN heating is the more important factor.

In all systems at early times there will be an abundance of cold gas and star formation. SNe will quickly heat pockets of gas to $T_{\text{SN}}$. If $M < M_*$ this gas will escape into the intergalactic medium (IGM), carrying off the bulk of the SN energy and much of the newly-synthesized elements. In clusters the significant metallicity of the X-ray emitting gas (which contains $\sim 4/5$ of the baryons and $\sim 1/2$ of the metals) is direct evidence that this happened. In systems with $M < M_*$ gravitational heating is ineffective, so alongside the outflow of SN-heated gas, there will be an inflow of cold metal-poor gas that continues to feed star formation.

Once $M > M_*$, the SN-heated gas cannot escape, although it can be pushed out of the region of most active star formation. There it will be joined by the now significant fraction of gravitationally heated gas. Over time a ‘cooling flow’ will develop. But, as we now know, the central BH will ensure that no stars form from this virialized gas. Cold gas continues to fall into the system, but, as in the Katz et al. simulations, at an ever-diminishing rate. Cold gas must enter as blobs and streamers; presumably blobs are often tidally disrupted into streamers. The orbits of infalling blobs will be determined by their angular momentum, which will on average increase over time, as material arrives that started out more and more remote from the centre of the system. Hence the fraction of the infalling blobs that penetrate the dense core of the cooling flow decreases over time.

The coexistence of hot and cold gas in pressure equilibrium is unstable: if the pressure is high, conduction of heat into the efficiently radiating cold gas will cause a steady transfer of gas from the hot to the cold phase, whereas if the pressure is low and radiation less efficient, the conductive heat flux will cause the cold gas to evaporate and join the hot phase. At each pressure there is a critical filament length $l_{\text{crit}}$ above which filaments condense hot gas and below which they are evaporated by conduction. [Nipoti & Binney (2004a) showed that in the very centres of cooling-flow clusters, where cold filaments are observed,
$l_{\text{crit}} \approx 10 \text{kpc}$, while elsewhere $l_{\text{crit}}$ is so large that it is not surprising that there are no surviving filaments. Hence this line of argument not only allows us to explain why we only see H$\alpha$ filaments very close to the centres of cooling-flow clusters, but also explains why star formation is confined to these regions also: the atmosphere of gas at $T_{\text{vir}}$ cuts off the supply of cold gas by transferring to infalling protogalactic material energy generated by the nuclear BH. The fact that filaments contain normal dust (Sparkes, Macchetto & Golombek 1989), which condensed virial-temperature gas would not, supports the role of cold inflow in the formation of filaments.

5. The mass function of DM halos and the luminosity function of galaxies

Although in conventional CDM cosmology all galaxies form by the accumulation of baryons in DM halos, the luminosity function of galaxies is profoundly different from the mass function of DM halos. The latter is very nearly a power law $dN/dM \propto M^{-2.17}$ in the mass range of interest, while the luminosity function of galaxies is a much flatter power law for $L < L^*$ and then cuts off with almost exponential steepness. The characteristic luminosity $L_*$ coincides rather exactly with the luminosity of the Milky way, which has a baryonic mass $\sim M_*$.

From the earliest days of the CDM theory it has been clear that the steep slope of the DM mass function must be reconciled with the flat slope of the luminosity function by the efficient ejection of gas from shallow potential wells. SN-driven winds are prime candidates for this job, but gas is probably removed from the shallowest wells at very early times by photoelectric heating (Efstathiou 1992) and thermal conduction (Dekel 2004). Ab initio simulations of galaxy formation in the CDM picture have struggled to produce efficient mass ejection, but this is generally ascribed to inadequate spatial resolution, and the semi-analytic galaxy-formation codes that are widely used to connect observations to N-body simulations of invisible DM assume that ‘feedback’ from star formation to the ISM is efficient.

Benson et al. (2003) show that in the convergence $\Lambda$CDM cosmology feedback of the required efficiency is problematic in that it leads to the formation of excessive numbers of very luminous and anomalously young galaxies: gas thrown out of small halos later finds its way into deep potential wells, where it cools to form stars. This problem is eliminated once we recognize that these deep potential wells are precisely those possessed of AGN-thermostated ‘cooling flows’. Hence the late-infalling baryons that plague the Benson et al. models do not lead to the formation of ultraluminous galaxies, but simply extend the X-ray emitting atmospheres of groups and clusters.

6. Formation of disk galaxies

This meeting is about gas found away from the planes of disk galaxies. So how do disk galaxies fit into this picture?

The age distribution of stars near the Sun indicates that stars have formed at an approximately steady rate for $\gtrsim 10 \text{Gyr}$ (Binney, Dehnen & Bertelli 2000; Nordström et al. 2001). This phenomenon suggests that the solar neighbour-
hood has been accreting gas steadily over this period – if it were simply using an initial stock at a steady rate, not only would there be many more metal-poor G-dwarf stars than are observed, but it would be hard to understand why the strongly Jeans-unstable gas-rich early disk did not form stars much more rapidly than the relatively stable gas-poor current disk does.

Given the evidence presented above, it seems reasonable to assume that most of the infalling gas arrived cold rather than gravitationally heated to $T_{\text{vir}}$. In support of this assumption we have the result of Benson et al. (2000) that the contrary assumption of White & Rees leads to predicted soft X-ray luminosities of edge-on disk galaxies that are factors of several too large.

We do not understand how gas joins the disk, but we have good reason to believe that in general it arrives with an angular-momentum vector that is inclined to the disk’s symmetry axis, specifically:

- One explanation of the ubiquitous warps of HI disks (and the rarer warps in stellar disks) is that the torque generated by the deviation from planarity is associated with the exchange of angular momentum between the inner disk and the periphery, the angular momentum of which is dominated by contributions from recently accreted material (Ostriker & Binney, 1989; Jiang & Binney, 1999). Although we still lack a clinching argument for the correctness of this theory, all competing theories of warps have been ruled out.

- The angular momentum in the Magellanic Stream is comparable to that in the Galactic disk, and the two vectors are nearly perpendicular. The Sagittarius Dwarf has an intermediate stellar population so it must have started out in possession of interstellar gas. This has by now been stripped and will have contributed angular momentum in the direction that is perpendicular to both the disk and the orbit of the Magellanic Stream.

- Polar ring galaxies sometimes have much more angular momentum in the ring than in the perpendicular disk (Iodice et al., 2003).

- The famous galaxy NGC 4550, which has two coextensive stellar disks that rotate in opposite senses (Rubin, Graham & Kenney, 1992), must have formed through the accretion by a disk galaxy of gas that had angular momentum in the opposite direction to the galaxy’s existing angular momentum.

- The standard theory of overdensities in a Gaussian random field predicts that the angular momentum vector of infalling matter changes direction by of order a radian in a Hubble time (Quinn & Binney, 1992).

Infall of material with inclined angular momentum will clearly generate extra-planar gas.

There is now compelling evidence that the inner part of the Milky Way’s bulge is blowing a wind (Bland-Hawthorn & Cohen, 2003). This is as expected for a spheroidal system with $M < M_\ast$. Somewhere there must be a transition between a wind from the nucleus and infall to the disk. Moreover there is likely to be mass and energy exchange between the two flows. As evidence of this
exchange, one may cite the metallicities of high-velocity clouds \cite{Wakker, 204}. The available measurements indicate values of \( Z \sim 0.2Z_\odot \) that are much lower than the expected metallicity \( (Z > Z_\odot) \) of the nuclear wind, but higher than the expected metallicity \( (Z \sim 0.01Z_\odot?) \) of primordial gas.

7. Conclusions

We have seen evidence (i) that feedback is efficient, (ii) that the nuclear regions of spirals are blowing winds, (iii) that galaxies form from cold infall, (iv) that the disks of spirals are still forming, (v) by acquiring gas that has angular momentum that is not parallel to the disk's angular momentum. When we put these pieces together it is clear that we expect there to be extraplanar gas, and that we cannot hope to understand the dynamics of this gas without taking into account the way in which it interacts both with the nuclear wind and with cosmic infall. Conversely, studies of extraplanar gas provide leverage on the central problem of understanding how the Universe came to be structured as it is.

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