Are galactic coronae thermally unstable?

Carlo Nipoti

Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy

Abstract. A substantial fraction of the baryons of disk galaxies like the Milky Way is expected to reside in coronae of gas at the virial temperature. This is the only realistic reservoir of gas available to feed star formation in the disks. The way this feeding occurs depends crucially on whether galactic coronae can fragment into cool clouds via thermal instability. Here I summarize arguments suggesting that galactic coronae are not prone to thermal instability, and I briefly discuss the implications for galaxy-formation models and for the origin of the high-velocity clouds of the Milky Way.

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CORONAE OF DISK GALAXIES

Milky Way-like galaxies are expected to be surrounded by hot rarefied gas halos, often referred to as galactic coronae [1]. These galactic coronae are hidden, in the sense that we have only indirect evidence that they exist, so their physical properties, such as density profile and angular momentum, are very poorly constrained. Indications in favour of virial-temperature \((T \sim 10^6 \text{ K})\) gas around the Milky Way are, for instance, the requirement of confinement of the high-velocity clouds (hereafter HVCs) [2], the morphology of the HVCs [3] and the presence of ultraviolet absorption lines in the direction of the HVCs [4].

The Milky Way has been forming stars at a rate of \(\sim 1M_\odot/\text{yr}\) for a few gigayears, and the same rate of gas accretion is needed to feed star formation [5]. Where does the gas feeding star formation come from? Accretion of cold gas from satellites is not enough [5], so the galactic corona is the only realistic reservoir of gas. The question is how the hot gas is converted into cool gas useful for star formation. In the classical picture of galaxy formation [6], all the gas within the cooling radius cools monolithically to form a galactic disk. However, this scenario is not completely satisfactory, in particular because it is affected by the so-called over-cooling problem (the predicted fraction of condensed baryons is substantially larger than the actual fraction) and by the angular-momentum problem (galaxies are predicted to have too low angular momentum) [7], and because it has difficulties in reproducing the observed galaxy luminosity function [8].

In order to solve these problems, an alternative “multi-phase cooling” galaxy-formation scenario has been proposed [9], in which it is assumed that the hot gaseous halos of Milky Way-like galaxies are thermally unstable, so that they do not cool monolithically, but fragment into cool \((T \sim 10^4 \text{ K})\) pressure-supported clouds. Star formation in the disk would be fed by these cool clouds, which, in the case of the Milky Way, should be identified with the HVCs. Support for this scenario comes from numerical
simulations based on the smoothed particle hydrodynamics (hereafter SPH) method \[10, 11\]. However, given the known difficulties of simulating with SPH a multi-phase medium with strong density gradients \[12, 13\], it is debated whether the results of these simulations are reliable or significantly affected by numerical effects.

In fact, an independent argument, based on studies of the cooling flows in clusters of galaxies, would suggest that galactic coronae should not be thermally unstable. Thermal instability is the physical process underlying the so-called “distributed mass drop-out” model proposed in the attempt of solving the cooling-flow problem of clusters of galaxies \[14\]. The viability of the distributed mass drop-out model was soon questioned on the basis of analytic calculations showing that the intra-cluster medium (ICM) cannot condense into cool clouds far from the center of the cluster, because it is thermally stabilized by buoyancy and thermal conduction \[15, 16\]. Galactic coronae are similar in many respect to the ICM, but have substantially lower gas temperature and density, and might be characterized by non-negligible rotation. Provided that these differences are taken into account, the problem of thermal instability of galactic coronae can be studied analytically as done for the ICM. Here I report some recent results of such analytic calculations.

**THERMAL-STABILITY ANALYSIS: NON-ROTATING CORONAE**

Binney et al. \[17\] performed a thermal-stability analysis of galactic coronae, by applying the Eulerian plane-wave perturbations approach used by Malagoli et al. \[15\] in studying cooling flows in galaxy clusters. The corona is modeled as a non-rotating, quasi-hydrostatic, stratified gas in the presence of cooling and thermal conduction. The atmosphere is considered unmagnetized in the sense that ordered magnetic fields are neglected (which should be a reasonable approximation, at least far from the disk), while tangled magnetic fields have the only effect of suppressing thermal conductivity below Spitzer’s benchmark value. An analytic dispersion relation can be obtained, so that the linear evolution of a perturbation of given wave-vector is fully determined by the physical properties of the corona.

Though the behavior of a given perturbation depends on the properties of its wave-vector (tangentially-oriented perturbations have more chances to grow than radially-oriented perturbations \[15, 17\]), the stability of the system is basically determined by three relevant timescales: the thermal instability time \(t_{th}\) (of the order of, but typically shorter than the cooling time), the Brunt-Väisälä (buoyancy) time \(t_{BV}\), and the thermal-conduction time \(t_{cond}\). The system is unstable only when the thermal-instability time \(t_{th}\) is shorter than the buoyant oscillation time \(t_{BV}\), and the thermal-conduction time \(t_{cond}\). The system is unstable only when the thermal-instability time \(t_{th}\) is the shortest: when \(t_{BV}\) is shorter than \(t_{th}\) buoyant oscillations dominate and the system is over-stable; when \(t_{cond}\) is shorter than \(t_{th}\) the system is stable. In particular, thermal conduction damps perturbations with wave-length \(\lambda\) shorter than a critical wave-length, which is longer for higher gas temperature.

Let us focus on the Milky Way: given the relatively poor observational constraints available, it is possible to construct quite different models of the Galactic corona, ranging from isothermal to adiabatic distributions \[17\]. Applying the results of the linear-perturbation analysis to these models Binney et al. \[17\] found that an isothermal corona is not prone to thermal instability, because at all radii \(t_{BV} \ll t_{th}\), so buoyancy
leads to over-stability rather than instability; in addition short-wavelength perturbations ($\lambda \lesssim 10$ kpc at distances $\gtrsim 100$ kpc from the Galactic center) are damped by thermal conduction. Only strictly adiabatic coronae can be unstable (the entropy profile is flat, so $T_{BV} \rightarrow \infty$), but also in this case thermal conduction has a stabilizing effect on short-wavelength perturbations. Note that damping by thermal conduction is important even if conduction is suppressed, by tangled magnetic fields, to $\sim 1/100$ of Spitzer’s fiducial value.

**EFFECT OF ROTATION**

Galactic coronae might be characterized by non-negligible rotation, so a natural question to ask is whether rotation can affect their thermal-stability properties. In the absence of rotation, and for outward-increasing entropy profiles, thermal perturbations are stabilized by buoyancy. It is well known that there is an interplay between convective stability and rotation, so also the evolution of thermal perturbations might depend on rotation. In particular, if rotation stabilizes against convection we might expect that it destabilizes thermal perturbations, because it reduces the stabilizing effect of buoyancy. Therefore, a first qualitative indication about the effect of rotation on the thermal instability of galactic coronae can be obtained by considering the results of studies of convection in rotating stars. Almost sixty years ago, Cowling [18] showed that rotation has a stabilizing effect against convection for axisymmetric perturbations (a consequence of angular momentum conservation), but not necessarily for non-axisymmetric perturbations: in general the stabilizing effect of rotation is less in the latter case and it disappears for specific perturbations. This argument suggests that rotating galactic coronae (in the absence of thermal conduction) might be thermally unstable against axisymmetric perturbations, but still stabilized by buoyancy against non-axisymmetric perturbations, provided that the distribution has outward-increasing entropy profile. In any case thermal conduction can stabilize the system. Preliminary results of a quantitative thermal-stability analysis of rotating stratified atmospheres confirm these expectations [19]. For the considered problem of condensation of cool clouds from the hot corona, we are interested in the behavior of non-axisymmetric perturbations: in this case the results obtained in the absence of rotation could hold also in the case of rotating coronae.

Recently, Kaufmann et al. [20] explored the problem of the thermal stability of galactic coronae via high-resolution SPH-based numerical simulation: the initial corona models have non-zero angular momentum, but the effect of thermal conduction is not accounted for in the simulations. Consistent with the above analytic results, Kaufmann et al. [20] find that thermal instability operates only in coronae with very shallow specific-entropy profiles, while no cool clouds form in standard coronae with steep outward-increasing specific entropy profiles.

**CONCLUSIONS**

The results reported above lead to the conclusion that multi-phase cooling and formation of HVCs by thermal instability are unlikely to occur in galactic coronae. In general the
The corona is stabilized against thermal perturbations by buoyancy, unless it is perfectly adiabatic, in which case it is effectively stabilized by thermal conduction. If thermal instability is not at work, alternative mechanisms must be responsible for the formation of the HVCs and for feeding star formation in the disks of galaxies like the Milky Way. While HVCs probably form via accretion and stripping of gas-rich satellites, the gas responsible for feeding star formation must ultimately come from the corona. Marinacci et al. [21] propose that the galactic fountain is the link between the coronal gas and the disk: in this picture fountain clouds grab coronal gas along their orbits via turbulent mixing, thus continuously bringing to the disk fuel for sustaining star formation.

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