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NEW PROBLEMS FOR THE FORMATION OF DISK GALAXIES

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RESUMEN

Analizo el papel que juega el momento angular en la formación de galaxias de disco, y describo el resultado de dos estudios encaminados a comprobar el paradigma estándar para la formación de discos.

ABSTRACT

I discuss the role of angular momentum in the formation of disk galaxies, and describe the results of two studies aimed at testing the standard paradigm for disk formation.

Key Words: **DARK MATTER — GALAXIES: FORMATION — GALAXIES: STRUCTURE**

1. INTRODUCTION

The current paradigm for disk formation contains three important ingredients: (i) the angular momentum originates from cosmological torques; (ii) the gas and dark matter within virialized systems have initial angular momentum distributions (AMDs) that are identical; and (iii) the gas conserves its specific angular momentum when cooling. Under these assumptions the predicted scale lengths of disk galaxies are in excellent agreement with observations (Fall & Efstathiou 1980; de Jong & Lacey 2000), which has motivated the construction of more detailed models, but always under the three assumptions listed above (e.g., Mo, Mao & White 1998; van den Bosch 1998, 2000, 2001, 2002; Firmani & Avila-Reese 2000).

Because of the overall success of these models in explaining a wide range of observed properties of disk galaxies, it has generally been assumed that the aforementioned assumptions are correct. However, several recent results have started to cast some doubt as to the validity of this standard framework. First of all, detailed hydro-dynamical simulations of disk formation in a cold dark matter (CDM) Universe yield disks that are an order of magnitude too small (e.g., Steinmetz & Navarro 1999). This problem, known as the angular momentum catastrophe, is a consequence of the hierarchical formation of galaxies which causes the baryons to lose a large fraction of their angular momentum to the dark matter.

Secondly, under assumption (iii) the density distribution of disks is a direct reflection of the AMD in the proto-galaxy. Bullock et al.(2001, hereafter B01) determined the AMDs of individual dark matter halos, which according to assumption (ii) should be identical to that of the gas, and thus to that of the disk. However, these distributions seem to have far too much low angular momentum material for consistency with the typical exponential density distributions of disk galaxies (B01; van den Bosch 2001).

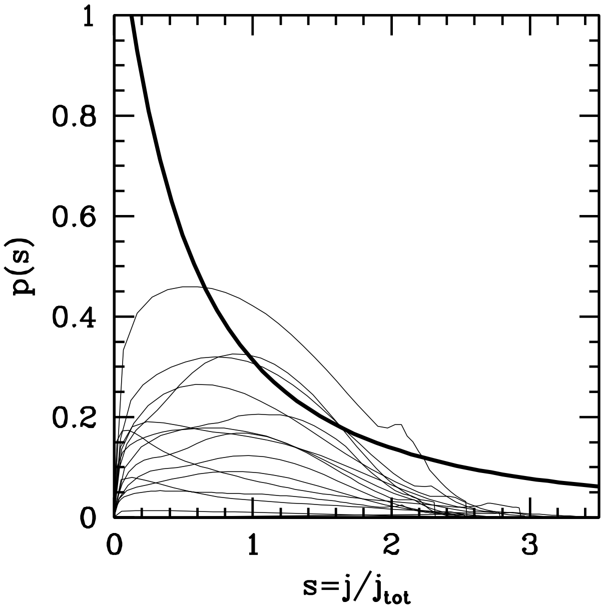

Fig. 1. A comparison of the AMDs of 14 disk galaxies (thin lines) with those of CDM halos (thick line) as parameterized by the ‘universal’ profile introduced by B01. Whereas the latter is normalized to unity, the former are normalized to the ratio of disk mass to expected baryon mass (i.e., the universal baryon fraction times the total virial mass). As is evident, only a small fraction of the baryons within the halo’s virial radius have ended up in the disk, and with a AMD that strongly differs from that of the ‘universal’ distribution for CDM halos.

2. TESTING THE PARADIGM

If assumption (ii) and (iii) are correct, *and all baryons inside the virial radius make it into the disk*, the AMD of a disk galaxy should be identical to that of the “universal” profile suggested by B01. In van den Bosch, Burkert & Swaters (2001), we computed the AMDs of 14 dwarf galaxies for which accurate photometry and kinematics are available. The results are shown in Figure 1. Two characteristics are apparent. First of all, only a small fraction (between 2 and 75 percent) of the available baryons have ended up in the disk: the remaining gas has either not yet cooled, or has been expelled from the disk through feedback processes. Secondly, the AMDs of the disk differ strongly from that of the dark matter halos. This suggests that either preferentially the low-angular momentum gas has been prevented from ending up in the disk galaxy or the gas and dark matter started out with different angular momentum distributions. The former might be established by a specific kind of feedback, while the latter would imply inconsistency with assumption (ii) of our standard framework for disk formation.

Therefore, in order to test whether indeed the gas and dark matter acquire identical AMDs van den Bosch et al.(2002) performed numerical simulations of structure formation in a ΛCDM cosmology including both dark matter (DM) and a non-radiative gas. For each halo in this simulation we computed the AMDs of both the gas and the associated dark matter. A detailed investigation of these AMDs leads to the following two conclusions:

- The gas and DM have virtually identical AMDs
- Between 10 and 40 percent of the gas has negative specific angular momentum (w.r.t. the total angular momentum vector).

The former indicates that assumption (ii) in the standard paradigm of disk formation is correct. However, since disk galaxies in general do not contain significant amounts of counter-rotating material, *disk formation cannot occur under detailed conservation of specific angular momentum of the baryons*, in conflict with assumption (iii).

3. DISCUSSION

Since the seminal paper by Fall & Efstathiou (1980), a standard model for the formation of disk galaxies has been around that describes disk formation in terms of the way gas acquires, and subsequently conserves, specific angular momentum. Surprisingly enough, very little attention has been paid to testing the validity of the underlying assumptions. Via numerical simulations we have shown, for the first time, that in accord with this standard framework, gas and dark matter acquire identical AMDs. However, the fact that these AMDs reveal large mass fractions with *negative* specific angular momentum implies that the gas cannot conserve its detailed distribution of specific angular momentum when cooling to form the disk. This crumples one of the main pillars of our standard picture, and indicates that a new spin on the angular momentum acquisition of disk galaxies may be required.

Additional puzzles come from the fact that the AMDs of observed disk galaxies are dramatically different from those of dark matter halos: disk predominantly lack low angular momentum material. Furthermore, detailed numerical simulations of disk formation that include cooling find a large transfer of angular momentum from the gas to the dark matter, resulting in disks that are an order of magnitude too small. It is currently unclear whether these puzzles indicate a fundamental problem for the theory or merely for the particular way in which feedback processes are implemented (or ignored) in the current simulations and/or models for disk galaxy formation. A first-order attempt to address the impact of feedback processes on the angular momentum of the gas in proto-galaxies is presented in Abel et al.(2002), where it is shown that any feedback process capable of expelling baryons from dark matter halos, is likely to decouple the angular momentum of the gas from that of the baryons.

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