Specific Angular Momentum Distribution of Disc Galaxies Formed in Preheated Intergalactic Media *

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Assuming that baryons within a galactic halo have the same specific angular momentum as the dark matter where they locate initially and a disc forms due to the gas cooling and condensation with the conservation of angular momentum, we investigate the angular momentum distribution in a resulting galactic disc under the new preheated galaxy formation model suggested by Mo and Mao (Mon. Not. R. Astron. Soc. 333 (2002) 768). Compared with the observational results, it can be concluded that the preheated galaxy formation model can match current observations. This model can be a good approach to solve the problems of both the angular momentum catastrophe and the mismatch of angular-momentum profiles in current disc galaxy formation models.

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According to the current paradigm of galaxy formation within the cold dark matter (CDM) model, expected by White and Rees[1] and Fall and Efstathiou,[2] disc galaxies are assumed to be formed by the cooling and condensation of baryons within dark matter halos (http://center.shao.ac.cn:1000/attachomentum (AM)). In this scenario, the major properties of a disc galaxy such as mass and surface density profile, etc. are determined by the properties of its host halo. The resulting disc galaxy population can match observations very well, such as the distributions of disc sizes, kinematics, colours and morphologies.[3−12] However, detailed studies in recent years show that there exist discrepancies between model predictions and observations. For instance, it is found from numerical simulations that the resulting disc sizes could be an order smaller than observations due to the transfer of AM between baryons and dark matter, which is called the angular momentum catastrophe (for details see Ref. [13]). Furthermore, it is noted that the observed distributions of specific angular momentum (SAM) of disc galaxies are quite different from those predicted by N-body simulations,[14] which is called the mismatch of angular-momentum profiles.[15,16] In our previous paper,[17] we found that a larger mass fraction of baryons with low angular momentum is predicted theoretically than that observed for our Milky Way Galaxy.

Great efforts have been exerted to this field. Van den Bosch *et al.*[15] (hereafter V01) pointed out that cooling, feedback, stripping and viscosity, which are the main mechanisms to change the distributions of AM of baryons in discs, seem to be unable to explain such large discrepancies. Chen *et al.*[18] suggested that baryons within a halo can be divided into cold and hot phases initially, which correspond to the later formation of the bulge and disc, respectively. The AM of baryons in hot phase is larger than that predicted by Bullock *et al.*[14] (hereafter B01). Thus there might not be such serious discrepancies between the CDM model and observations. Moreover, galactic winds with mass outflows driven by supernovae explosion in the disc, which is significant for high redshift galaxies, will make the distribution of SAM in discs different from the initial ones.[19] However, detailed calculations[4] showed that it is still far from satisfactory. Maller *et al.*[20] proposed an alternate algorithm for the buildup of halo spin by summation of the orbital angular momenta of merging satellites including supernovae feedback, and their model of halo spin buildup is quite different from the common one which is generally believed to arise from cosmological tidal torques.

Recently, Mo and Mao[21] (hereafter M02) suggested a model of galaxy formation in which baryons within a galactic halo was preheated to high entropy by vigorous energy feedback associated with the formation of stars in old ellipticals and bulges and with AGN activity. Therefore, the initial density profile of baryons is not the same as the usual assumption in current galaxy formation and evolution theory that baryons trace the same density profile as the dark matter. Their model may provide a new method to solve the AM problems in current disc galaxy formation theory.

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In this Letter, we follow the preheated model of galaxy formation suggested by M02 to show whether the SAM distribution of baryons in a resulting galactic disc can match observations. As in our previous paper,[17] star formation is not included simply, and the SAM distribution of baryons within a halo is assumed to be the same as dark matter suggested by B01 where they located initially. A disc will form due to the radiative cooling of baryons under the conservation of their AM. We adopted a ΛCDM cosmogony with $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 100h\,\mathrm{km\,s^{-1}Mpc^{-1}}$. Whenever a numerical value of h is needed, we take $h = 0.7$.

The density profile of a dark matter halo is adopted as the Navarro–Frenk–White (NFW) profile [22]

$$\rho(r) \propto \frac{1}{(cx)(1+cx)^2}, \quad x \equiv r/r_h, \tag{1}$$

where r_h is the virial radius of the halo which is $r_h = V_c/10H(z)$ with V_c and $H(z)$ being the halo circular velocity and the Hubble constant at redshift z, while c is the concentration parameter which is taken to be 10 as its median value for the CDM model.[23]

The total angular momentum of a halo can be well described by a dimensionless spin parameter λ, which is the ratio of its rotational energy to bounding energy. According to numerical simulations,[24–27] λ shows a log-normal distribution for the galaxy population

$$p(\lambda)d\lambda = \frac{1}{\sqrt{2\pi}\sigma_\lambda}\exp\Big[-\frac{\ln(\lambda/\overline{\lambda})}{2\sigma_\lambda^2}\Big]\frac{d\lambda}{\lambda} \tag{2}$$

with $\overline{\lambda} = 0.05$ and $\sigma_\lambda = 0.5$, respectively. We take $\lambda = 0.05$ in the present Letter. According to their high-resolution N-body simulations, B01 suggested a universal SAM distribution for a galactic halo in cylindric coordinate, which is

$$M(<j) = M_h\frac{\mu j}{j_0 + j}, \quad \mu > 1 \tag{3}$$

where $M(<j)$ is the halo mass with SAM less than j, while $j_0 = j_{\max}(\mu - 1)$ with $j_{\max}$ being the maximum SAM of the halo, and μ is called the shape parameter. B01 found that $\mu - 1$ displays as a log-normal distribution with a median value of 1.25. The range $1.06 < \mu < 2.0$ covers 90 percent of the halo population. Here we choose $\mu = 1.25$.

According to M02, the preheated baryonic density profile within the virial radius of a halo can be written as

$$n^{2/3}(r) = \overline{n}^{2/3} + \frac{4}{5}\frac{\mu m_p V_c^2}{2k\mathcal{S}}\Big(1 - \ln\frac{r}{r_h}\Big), \tag{4}$$

with the corresponding temperature profile

$$T(r) = \mathcal{S}n^{2/3}(r), \tag{5}$$

where $\overline{n}$ is the background baryon density, $\mathcal{S}$ is the entropy parameter, m_p is the proton mass, and μ is the mean molecular weights which is about 0.6 for the primordial composition. M02 showed that the entropy $\mathcal{S}$ is approximately conserved after redshift $z \sim 3$ because cooling is inefficient at low overdensities and at low redshift ($z \leq 3$) after comparing the cooling timescale due to radiation with the Hubble time. Here $\mathcal{S}$ can be determined from observations which is $\sim 100\,\mathrm{keV\,cm^2}$ in galaxy clusters and groups.

Moreover, the fraction of baryons inside the virial radius of a halo that have cooled down to form a disc by redshift z within a spherical mass shell is given by M02 as

$$\begin{aligned} f_{\rm cool}(z) \equiv \int\frac{dt}{t_{\rm cool}} &\approx 1.5\times10^{-3}h^{-1}\Big(\frac{\Omega_{b,0}h^2}{0.02}\Big) \\ &\cdot\int_{z_{\rm ph}}^{z}\frac{H_0 dt}{dz'}\frac{\Lambda_{-23}}{T_6}(1+\delta) \\ &\cdot[1 - f_{\rm cool}(z')](1+z')^3dz', \end{aligned} \tag{6}$$

where $\Omega_{\rm b,0}$ is the baryonic density at present day which is chosen as $f_{\rm b}\Omega_0$ with $f_{\rm b} = 0.1$,[28] $z_{\rm ph}$ is the redshift at which the gas has been preheated, δ is the density contrast, $T_6 \equiv T/10^6\,\mathrm{K}$, Λ_{-23} is the cooling rate in units of $10^{-23}\,\mathrm{cm^3\,erg\,sec^{-1}}$ as defined in Sutherland and Dopita,[29] and the factor $[1 - f_{\rm cool}(z')]$ in the integrand takes into account the depletion. Based on observations, the bulk of preheating was likely to be around a redshift $z \sim 2 - 3$, where the cosmic star-formation rate and AGN number peak. As M02, here we let $z_{\rm ph} = 3$. It should be pointed out that the following calculation is carried out within the virial radius of a halo.

We divide a halo into many spherical shells. Equations (4) and (6) are adopted to obtain the mass of cooled gas within individual shells. The total amount of gas that has cooled is obtained through integrating all the spherical shells. It should be noted that the SAM of gas within a spherical shell is not the same everywhere, because the cylindrical distribution form of AMD is adopted here which is more reliable than that of the spherical AMD distribution.[14,17] The position in the disc where the cooled gas settles down is determined by the conservation of its AM.

As is performed by Van den Bosch *et al.*,[15] we let $p(j)\,dj$ indicate the fraction of mass with specific angular momentum between j and $j + dj$. The mass fraction with angular momentum less than a given value j then is

$$m(j) = \int_0^j p(j)dj. \tag{7}$$

The total specific angular momentum can be written as

$$j_{\rm tot} = j_{\max}\Big[1 - \int_0^1 m(l)dl\Big], \tag{8}$$

where $j_{\max}$ is the maximum specific angular momentum of $p(j)$, and $l = j/j_{\max}$. For comparison, we define that

$$s = j/j_{\rm tot}, \quad f_{\rm disc} = M_{\rm disc}/M_{\rm bar}, \tag{9}$$

where $M_{\rm disc}$ is the disc mass and $M_{\rm bar}$ is the total baryonic mass within a galactic halo.

In Fig. 1, the SAM distribution of a typical dark halo (with $c = 10$, $\lambda = 0.05$ and $\mu = 1.25$) in the ΛCDM model is plotted as the dotted lines, which has been normalized to unity. As an example, a disc galaxy with the halo circular velocity $V_{\rm c} = 170\,{\rm km\,s^{-1}}$, which corresponds to our Milky Way Galaxy or M31, is chosen for illustration of the preheated model. If the galaxy is formed in preheated intergalactic media, $p(s)$ versus s for the resulting disc is shown in the same figure as the solid lines, which is normalized by $f_{\rm disc}$. From the figure one can see that a large difference of the AM distribution in the resulting galactic discs between the preheated and no-preheated galaxy formation models exists, both of which have the same assumption that AM is conserved during the baryon cooling process. The resulting discs in the preheated model have lack of mass with low angular momenta.

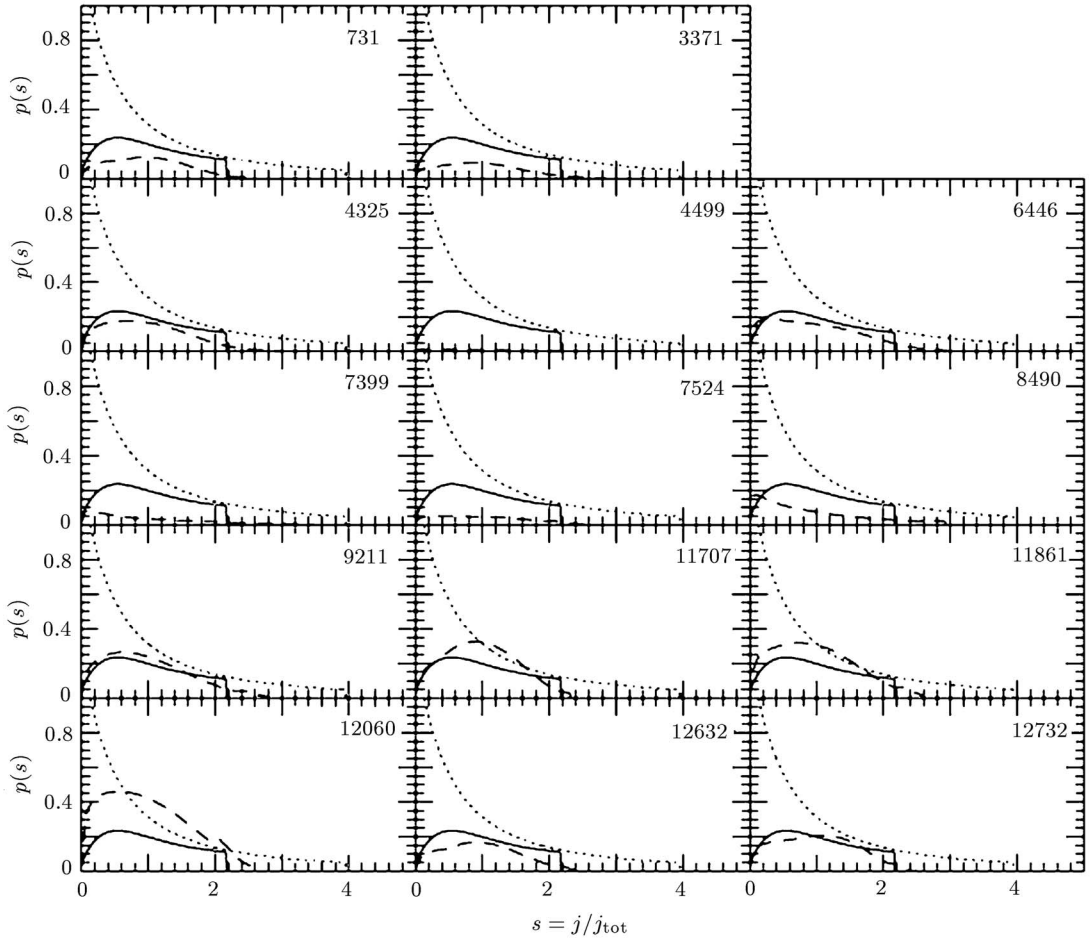

Fig. 1. Characteristics of $p(s)$ versus s with the dotted, solid and dashed lines denoting the angular momentum distributions of the dark matter halo, the resulting disc galaxy which form in the preheated intergalactic media, and the 14 galaxies observed by V01, respectively.

In 2001, van den Bosch *et al.*[15] presented the AM distributions for a sample of 14 dwarf galaxies with observed HI rotation curves, which are all within their corresponding virial radii defined above. The resulting $p(s)$ distributions from observations data for these 14 galaxies are shown as the dashed lines in Fig. 1, which are all normalized by their $f_{\rm disc}$, respectively. Comparing the observational and theoretical results, it can be concluded that the preheated galaxy formation model can provide a good approach toward the solutions of both the angular momentum catastrophe and the mismatch of angular-momentum profiles in the current disc formation models.

However, it should be pointed out that there are two kinds of uncertainties in this study. First, we assumed that the initial angular momentum of the baryons traces that of the dark halo. Cosmological hydrodynamical simulations[30] show that this may not

be the exact case although the angular momentum of baryons is similar to that of the dark halo when the effect of preheating is considered. This will not influence our conclusion very much. Higher resolution numerical simulations are still needed in the future. Moreover, it should be pointed out that the preheated gas density profile within a halo, i.e Eq. (4), is obtained by assuming that the dark matter halo has the density profile of a singular isothermal sphere. If the NFW profile is adopted, the prescription will be very complicated and there will be no analytic form for it. In this case the theoretical predictions in Fig. 1 will be different by only a factor of less than 15%, which would mean no significant changes to our results.

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