Simulations on the collisional properties of gas in galaxies

Yves Revaz & Daniel Pfenniger, Geneva Observatory, 51 Ch. des Maillettes, CH-1290 Sauverny, Switzerland

Treating correctly the physics of the interstellar medium (ISM) in galactic N-body models remains a challenging task. SPH methods allow to simulate highly collisional gas, while sticky particles techniques are appropriate for the much less collisional clumpy cold gas. In this work, we explore a simple method with few free parameters, which describes the global dynamical consequences on disk galaxies of a slow cycling of gas between the interstellar, almost collisionless very cold gas and the warm collisional phases, with a secular transformation of a fraction of warm gas into stars. This allows us to specify a range of conditions which are compatible with observational facts.

Model

Multiphase interstellar gas

Particles have been divided in three distinct components: the stars (ST), the warm gas (WG) and the dark gas (DG). Stars form the first collisionless component. The warm gas represents interstellar gas with a large range of temperature from 10 to 10^5 K. It contains fragmented dense molecular clouds that are the location of star formation as well as gas at higher temperature heated by the background UV radiation or by nearby star forming regions. The fractal structure of the ISM (Frail et al.[1994]) does not permit to assume it as a continuous collisional fluid. Standards methods like SPH are thus inappropriate and we have rather used the sticky particle scheme (Combes & Gerin [1985]) that is better suited to simulate the clumpy collisional structures. The DG represents the very cold hydrogen ($T < 10$ K) that is expected to exist in the outer disk of galaxies (Pfenniger et al. [1994]). It represents a substantial fraction of the dark matter and thus no further dark halo is used in this model. We assume that the very clumpy nature of the cold hydrogen makes this component behaves as collisionless.

Mass and energy exchanges

Mass exchange as well as transfer of energy between the three components are summarized on Fig. 1. Gaseous particles (WG and DG) can be heated by UV radiation of stars (including supernova feedback). The heating function depends on the distance between a star and a gaseous particle. WG particles are subject to cooling. Once a DG particle is heated it can becomes WG. Likewise, a cooling WG particle can become DG. Thus all along the simulation a mass transfer between the two phases occurs. Stars are created out of the WG component using a simple rule depending on the distance between two particles. It reproduces quite well the power Schmidt law with an exponent in the range $[1-2]$. The mass converted in stars is frozen in this component for the rest of the simulation. We take into account the dynamical feedback of the star formation by kicking gas particles around a new star. On the other hand, to keep the model simple, the mass feedback in form of stellar wind or SN ejection has been neglected.

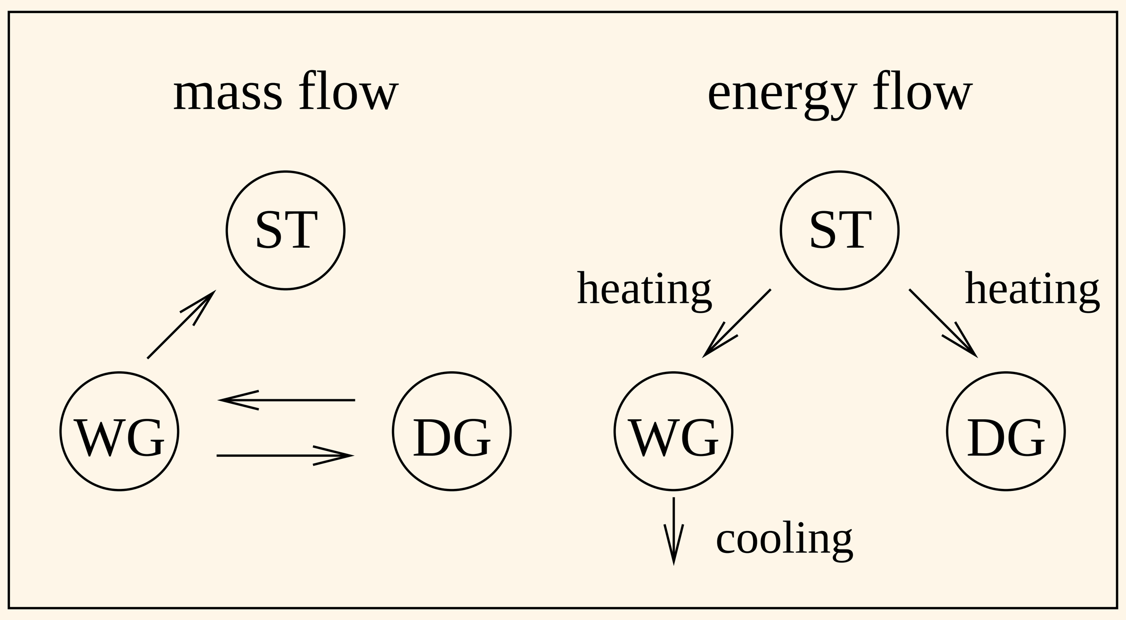

Fig. 1. Schema of mass and energy exchanges between the three components: ST=stars, WG=warm gas, DG=dark gas.

Dynamical cooling

The dissipative behavior of the warm gas has been computed following the sticky particle scheme. It is realized by adding a friction force between nearby particles. In order to conserve angular momentum the force must be central, i.e., aligned with the relative position of the two particles. The friction force acting on particle i due to the inelastic collision with particle j is given by:

$$\vec{F}^{\,\mathrm{fric}}_{j\to i} = \begin{cases} m_i\,\Lambda\,G(\Delta r)\,F(\Delta\vec{v},\Delta r)\,\vec{e}_{ji}, & \text{if } (\vec{v}_i-\vec{v}_j)\cdot\vec{e}_{ij} > 0 \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

m_i is the mass of particle i, Λ is the friction coefficient and $\vec{e}_{ji} = \frac{\vec{x}_i-\vec{x}_j}{|\vec{x}_i-\vec{x}_j|}$. G and F give respectively the dependence in position and velocities.

Initial mass distribution

As initial conditions we have used a simple model based on a Mestel disk. The surface density is given by:

$$\Sigma(R,z) = \Sigma_0\,\frac{e}{R+e}\,\mathrm{acos}\left(\frac{\mathrm{R}}{\mathrm{R_{max}}}\right). \qquad (2)$$

The initial radial scale length e, increases the surface density at the center and thus avoids the numerical instability of a pure Mestel disk. The initial vertical profile of is homogeneous between $\pm z_{\max}(R)$ where $z_{\max}(R)$ increases in function of R (flaring). All the matter is supposed to lie on the disk in form of dark gas. In order to ignite star formation 5% of the initial mass is in form of WG within 2 kpc.

Simulations

Numerical method

We have computed 11 models that explore the effect of the free parameters (heating, cooling, star formation, feedback) Model 00 is the reference model and its evolution is presented on Fig. 2. The code used is based on the Barnes-Hut *treecode* (Barnes & Hut [1986]) parallelized to run on our GRAVITOR Beowulf cluster. Each simulations contains 262′144 particles. The open angle criterion parameter has been fixed to 0.6 and the softening length ϵ is 0.15 kpc allowing a time step of 0.25 Myr.

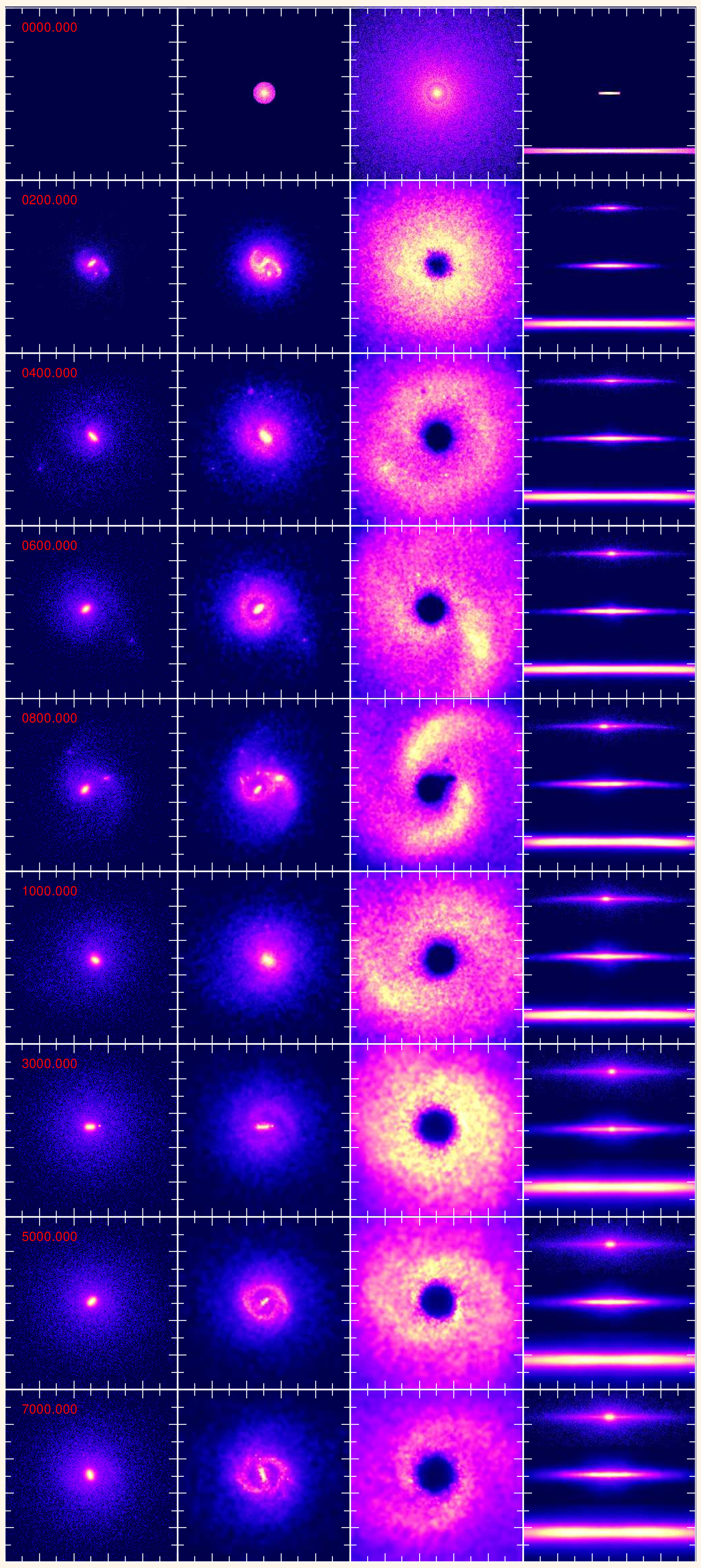

Fig. 2. Evolution of model between $t = 100$ and $t = 7000$ Myr. Columns 1 to 3 show respectively the face-on projection of stars, hot gas and cold gas. Column 4 shows an edge-on projection for each of the three components. The box dimensions are 50×50 kpc

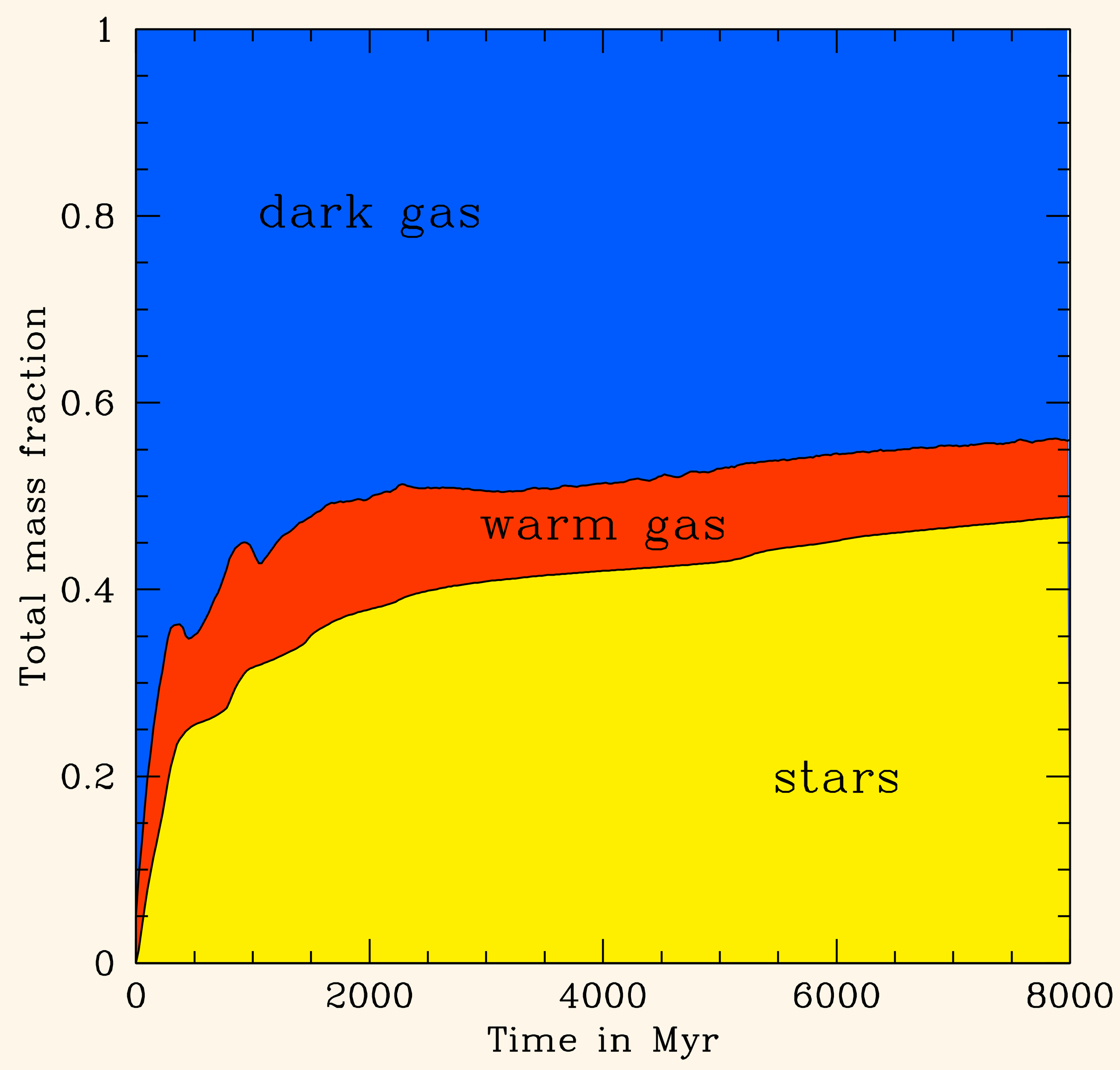

Fig. 3. Evolution of the mass fraction for the three components.

Results

Global evolution

The global evolution of the three components are displayed on Fig. 2. Soon after the beginning of the simulation ($t = 350$), the galactic center is subject to an instability. A bar forms and persists during the whole simulation. Spiral structures as well as rings are observable in the WG. Both are the location of higher SFR. At the center of the galaxy, the radiation field produced by the stars maintains the gas in a warm phase. The DG is thus eliminated from this regions and a hole of radius 6.5 kpc is dug (third column of Fig. 2.). Large spiral patterns are continuously produced in the DG disk. If a small fraction of this component is considered as HI, resulting for example of the heating by cosmic rays, the HI map of our model will be comparable to the spiral pattern observed in HI disk of some blue compact dwarf galaxy like for example NGC 2915 (Masset et al. [2003]) or the Circinus galaxy (Jones et al. [1999]). The correspondance between our model and those observations let us think that HI disks can contain a large fraction of dark matter. On the edge-on views (fourth column) we can observe the grow of the stellar disk. The bulge is created during the first Gyr and is present only in the stellar component. Despite the lack of a hot dark halo, the massive dark disk remains stable over the 8 Gyr simulation time.

Mass fractions

We can follow the evolution of the mass fraction of the three components on Fig. 3. DG is quickly converted to WG and ST during the first 2 Gyr. During this period subject to instabilities, the star formation rate (SFR) is high and oscillates between 10 and 100 $\mathrm{M_\odot\,yr^{-1}}$. From $t = 2000$ to the end, while the fraction of WG remains constant, DG still feeds the stellar component. The transfer rate is about $3-5\,\mathrm{M_\odot\,yr^{-1}}$. The final mass fractions are 0.48 (ST), 0.08 (WG), 0.44 (DG).

Mass distribution and rotation curve

The top panel of Fig. 4 shows the surface density of the components at the end of the simulation. The stars form spontaneously an exponential disk of scale length 4.9 kpc (blue line) with a central bulge component at $R < 5$ kpc. At the center, where the SFR is highest the WG density (red line) is depleted. DG dominates at large radius ($R > 10$ kpc) and decreased sharply at $R < 6$ kpc, This is consistent with maximum disk models where the fraction of DM is small within the optical disk. Because of the central cusp, the circular speed is high (Fig. 4 middle), but the mean azimuthal velocity is much lower with a maximum at 200 km/s. It decreases slowly outside. The bottom of Fig. 4 shows the vertical scale height of the three components. The collisionless behavior of the DG makes it becomes slightly thicker than the cooling WG. The stellar disk shows a clear flaring.

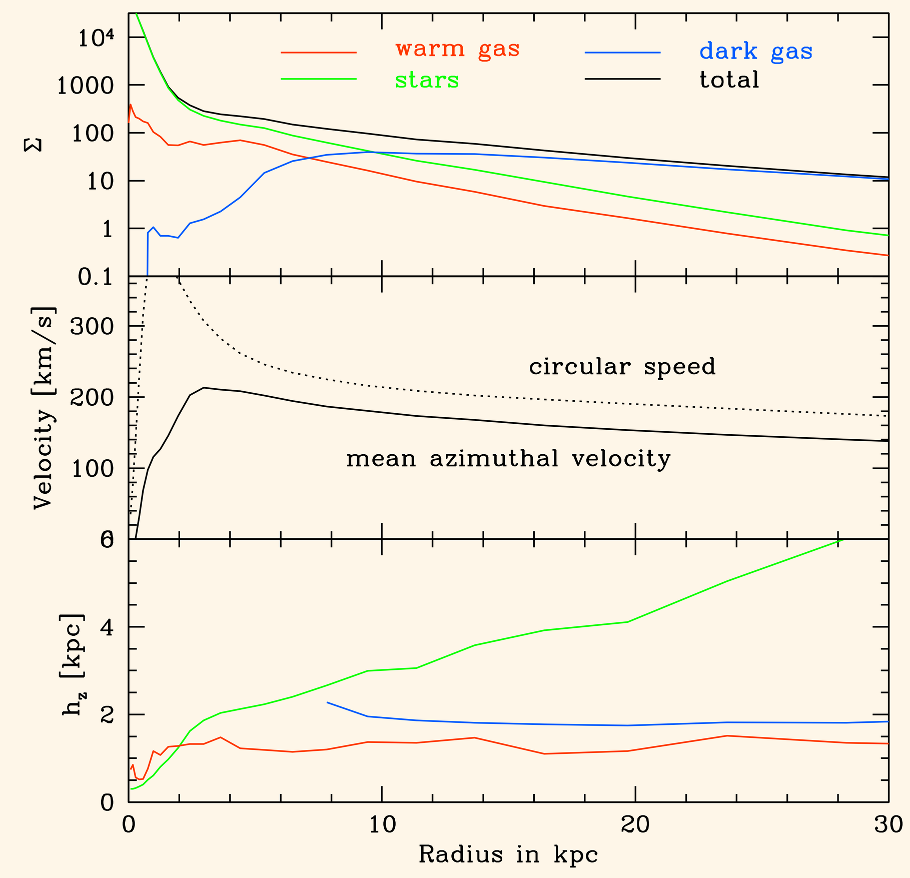

Fig. 4. Mass distribution and rotation curve at $t = 8000$. Top panel: surface density of the three components; Middle panel: circular speed (dotted line) and mean azimuthal velocity (solid line); Bottom panel: vertical scale height for the three components.

Conclusions

We have modeled the cycling between the stars, visible gas phase, and a very cold dark and collisionless gas phase with simple rules. Despite the lack of a classical dark matter halo, the presented model reproduces several typical features observed in spiral galaxies such as the stellar exponential disk within a bulge component, a typical mass fraction of visible gas, spirals in the gas, ring around the bar, the visible gas depletion in the central few kpc, as well as the lack of dark matter inside the optical disk consistent with maximum disk decompositions.

References

[1986] Barnes J., Hut P., 1986, Nature, 324, 446
[1985] Combes F., Gerin M., 1985, A&A, 150, 327
[1994] Frail D.A., Weisberg J.M., Cordes J.M., Mathers C., 1994, ApJ, 436, 144
[1999] Jones K., Koribalski B. et al., 1999, MNRAS, 302, 649
[2003] Masset F.D, Bureau M., 2003, MNRAS, 586, 152
[1994] Pfenniger D., Combes F., Martinet L., 1994, A&A, 285, 79