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We investigate the evolution of star-forming gas-rich disks, using a 3D chemodynamical model including a dark halo, stars, and a two-phase interstellar medium with feedback processes from the stars. We show that galaxy evolution proceeds along very different routes depending on whether it is the gas disk or the stellar disk which first becomes unstable, as measured by the respective Q-parameters. This in turn depends on the uncertain efficiency of energy dissipation of the cold cloud component from which stars form. When the cold gas cools efficiently and drives the instability, the galactic disk fragments and forms a number of massive clumps of stars and gas. The clumps spiral to the center of the galaxy in a few dynamical times and merge there to form a central bulge component in a strong starburst. When the kinetic energy of the cold clouds is dissipated at a lower rate, stars form from the gas in a more quiescent mode, and an instability only sets in at later times, when the surface density of the stellar disk has grown sufficiently high. The system then forms a stellar bar, which channels gas into the center, evolves, and forms a bulge whose stars are the result of a more extended star formation history.

We investigate the stability of the gas-stellar disks in both regimes, as well as the star formation rates and element enrichment. We study the morphology of the evolving disks, calculating spatially resolved colours from the distribution of stars in age and metallicity, including dust absorption. We then discuss morphological observations such as clumpy structures and chain galaxies at high redshift as possible signatures of fragmenting, gas-rich disks. Finally, we investigate abundance ratio distributions as a means to distinguish the different scenarios for bulge formation.

Introduction

The formation of galaxies is one of the important questions in current astrophysical research. With HST and earth-bound 10m class telescopes it is now possible to study the evolution of galaxies with redshift by direct observation. Although no complete picture is available at the moment, some facts are well established. Surveys undertaken around $z \approx 1$ have shown that luminous elliptical and spiral galaxies were largely formed by then, and have only moderately evolved to the present time brinchmann98, lilly98, abraham99, abraham99b, abraham00, dickinson00. Beyond $z = 1.4$, there are far fewer high-luminosity galaxies of all types compared to low redshifts (dickinson00, see also driver98). Thus the bulge-to-disk Hubble sequence of galaxies appears to have formed at redshifts slightly beyond $z \sim 1$ abraham00, kajisawa01, although part of the stellar populations of these galaxies might have formed earlier.

At $z \approx 0.5$ spiral galaxies and barred galaxies are observed, and it seems that by then the full Hubble sequence is in place, quite similar to the galaxy distribution today. However, the frequency of barred galaxies drops sharply beyond $z \approx 0.5$ abraham99. vdb02 showed that this is not an selection effect. They shifted a local galaxy sample to higher redshifts and concluded that most of the barred galaxies would still be visible. Thus, the absence of bars at higher redshifts seems to be real.

Already at $z \sim 1$ around 30% of galaxies are morphologically peculiar. At higher redshifts many clumpy structures and compact objects are observed. Most of these cannot be attached to the traditional Hubble scheme, but show irregular morphologies abraham99, vandenbergh00. The anomalous morphologies observed in these high redshift objects cannot be explained through band-shifting effects alone, because the irregularities persist also in NICMOS observations dickinson00, probing the visual restframe wavelength of these objects.

Observations of high redshift galaxies currently provide information only about the global properties of these objects. Detailed data like stellar metallicity distributions, stellar kinematics, or gas distributions are only available for local galaxies. To understand galaxy formation in a consistent picture, models must be developed that can be compared with observations over the whole observed redshift range. These models
should be able to explain the properties of distant galaxies as well as the detailed data on local galaxies.

With high resolution cosmological simulations, large progress has been made in understanding cosmic structure formation [e.g.,] navarro96, moore98, jenkins01, klypin01. However, on galactic scales these simulations still lack the necessary resolution to describe the processes relevant for baryon dissipation and star formation. Therefore two approaches for describing galaxy formation and evolution have been developed. Semi-analytical modeling, based on simple assumptions to describe the baryonic physics and star formation in the dark halos that form in the cosmological simulations, has been used to analyze the global properties of galaxy samples [e.g.,] kauffmann93, guiderdoni98, cole00.

On the other hand, dynamical models, using a subset of the cosmological information as initial conditions on smaller scales, have been used to investigate the detailed structure of forming galaxies [e.g.,] steinmetz95, navarro97b, sommer99, williams01, samland03. These small-scale dynamical models still need to describe star formation with a simple parametrization, but they contain a much more detailed description of the dynamics, feedback, and, in some cases, element enrichment. Thus with these models it is possible to predict observable properties through the galaxy assembly process, and to compare directly with observations of high redshift galaxies [e.g.,] contardo98, westera02, abadi03. Because these models can be calculated over a Hubble time, one can also directly compare detailed present-day characteristics (e.g., metallicities and kinematics of stellar populations) with observations of local galaxies. Finally, with such models predictions can be made for dynamical and stellar population properties of high-redshift galaxies, which can be verified by future high resolution observations with the next generation telescopes.

The mass accumulation into dark matter halos is well understood in the context of the cosmological simulations and can be used as an input to model galactic evolution [e.g.,] vdbosch02, wechsler02. Additionally, the angular momentum distributions of the forming dark halos have been calculated recently bullock01, chen02. It is widely accepted, both in the semi-analytical approach and the small-scale dynamical models, that galactic evolution depends sensitively on the mass and angular momentum distribution of the system.

Much less is known about the processes that govern the evolution of the baryons within a dark halo, and how these influence the properties of the forming galaxies. Stars in galaxies nearby are observed to form in molecular clouds much denser than the ambient medium in which these clouds are embedded. Most of the kinetic energy of this cloud fluid is in the motions of single clouds relative to the bulk flow. This kinetic energy can be dissipated by inelastic collisions larson69 and augmented by supernova feedback mckee77. Under some conditions the macroscopic cloud system can be treated as an isothermal fluid cowie80. Its energy dissipation rate is not well-determined, however. One expects that it depends on the geometrical structure of the clouds, on whether a major part of the dense medium is arranged in filaments, and on their self-gravitating structure and magnetic fields kim01, balsara01. Thus the dynamics of the macroscopic cloud medium may be more or less dissipative, depending on the physical conditions, and may well vary between galaxies.

In the present paper we investigate the formation and dynamical evolution of galactic disks, varying the cloud dissipation rate. We use the interaction network and two-phase chemodynamical model of [SG03]samland03 to describe the assembly of a disk of stars, hot gas, and star-forming cold gas. We find that the dynamical stability of the disk depends sensitively on the cloud dissipation efficiency, here described by the parameter $\eta_{\text{coll}}$. For large $\eta_{\text{coll}}$, dynamical instabilities in the gas dominate the evolution, leading to fragmentation of the disk into a small number of star-forming clumps which subsequently merge to form a centrally concentrated bulge. For small $\eta_{\text{coll}}$, on the other hand, the system forms stars until the stellar disk becomes unstable, leading to a stellar bar at late times. The different stability properties in both cases can be quantified in terms of the effective Toomre Q parameter for the stellar, gaseous, and combined system [e.g.,] toomre64, jog84, wang94, elmegreen95.

The evolution of a system with high dissipation calculated at higher resolution is described in immeli03, where it was shown that morphological and photometrical properties of several high redshift objects, like the chain galaxies cowie95, can be explained by a fragmented disk model.

Several authors have suggested that galactic bulges can form by the secular evolution of a galactic disk, driven by interstellar gas or stars [e.g.,] combes81, pfenniger90, noguchi99. Recent observations lend some support to these secular evolution scenarios. Bulges in late-type spirals show similar properties to their surrounding disks, in that their light profiles are better fit by an exponential rather than an $R^{1/4}$ law courteau96, seigar02, and in their colours peletier96.
As shown here, the evolution of star-forming galactic disks may take different routes, depending on whether it is the gas or the stars that drives a disk instability. This in turn depends on the uncertain efficiency of energy dissipation in the cold cloud component. These different routes also lead to different formation scenarios for galactic bulges. Thus we suggest here that the morphological properties of galaxies may depend not only on cosmological variables like different mass or angular momentum distributions, or infall history, but also on internal physical processes during galaxy evolution.

In Sect. modell we describe our model for star-forming disks. In Sect. morphologie we describe the morphological evolution of these disks, depending on the dissipation efficiency of the cold gas. Sect. globalevo discusses the stability and star formation rates in the models, and Sect. bulge describes the properties of the bulges that form in the two main evolutionary scenarios. Finally, Sect. concl summarizes our findings.

The Model modell

We use a two-phase model for the interstellar medium, consisting of a hot, low-density phase and a cold cloud medium from which stars are formed. The chemical elements and most of the energy released from SNeII and later SNeIa are returned to the hot phase. However, the cloud velocity dispersion of the cold phase is heated by SNeII as well mckee77. We describe this system with a three-dimensional chemodynamical evolution code, which combines a hydrodynamical grid code for the two phases of the interstellar medium (ISM) with a particle mesh code for the stars. See SG03 for more details.

The interactions between the different ISM phases and the stars are described in detail in SG03. A difference exists in the characterization of the star formation rate (SFR), where we use here a simple Schmidt law schmidt59, equationschmidt

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\dot{\rho}_{sf} = c_{sf} \cdot \rho_{\alpha cld}^{\alpha}
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