Galaxy simulations as a tool for mapping habitable zones

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ABSTRACT

The goal of Galactic habitability studies is to understand the spatial and temporal evolution of habitable environments in the Galaxy. To tackle this problem we are developing a methodology based on the combination of two different types of investigations. On the one hand, we investigate the effects of Galactic properties, such as metal abundances and star formation rates, on the formation and persistence of habitable environments. On the other hand, we use N-body simulations to map the spatial and temporal evolution of physical and chemical properties of a disk galaxy like the Milky Way. Here we present a brief description of the method and some preliminary results. In the first part we investigate the link between metallicity and probability of planet formation, based on measurements of dust-to-gas ratios in metal-poor galaxies observed in their early stages of evolution (Vladilo, 2004). In the second part we describe the Galactic simulations, performed with the code GADGET-2 in which we have recently implemented a chemical evolution model that allows us to obtain maps of metallicity (Tornatore et al., 2007). Combining these two investigations, we plan to convert the maps of metallicity into maps of probability of having star systems with planets. Together with our maps of star formation rates and supernovae explosions, we will obtain in this way maps of habitable zones.

What follows is a slightly extended version of the poster presented at the ISSOL 08 conference.

1. Metallicity and probability of planet formation

The metallicity is considered to be an important parameter in studies of Galactic habitable zones (GHZ; Gonzalez, Brownlee & Ward, 2001). The metallicity is defined here as M = [Fe/H] = log(Fe/H) – log $(Fe/H)_{SUN}$, where (Fe/H) is the number ratio measured, or predicted, in the region of interest and $(Fe/H)_{SUN}$ is the reference ratio in the Sun. Statistical studies of exoplanets indicate that the frequency of detection of giant planets increases with the metallicity of the star (Santos, Israelian & Mayor 2001; Fischer & Valenti, 2005). On the basis of this result, the probability of formation of planets, including the terrestrial ones, has been assumed to increase with the metallicity (Lineweaver, 2001). This assumption has been criticized because the statistics of terrestrial planets, as opposed to giant planets, is still unknown (Prantzos, 2007). The limited range of M covered so far by studies of exoplanets prevents to derive conclusions about the probability of planet formation when $\mathsf{M} < -0.6$ dex. Here we provide new arguments suggesting that the probability of planet formation may decrease abruptly at metallicities $\mathsf{M} < -1.5$ dex, for any type of planet assembled via accretion of rocky planetesimals.

1.1 The solid-to-gas mass ratio in the early stages of galactic evolution

The metallicity of the interstellar medium (ISM) increases with time and decreases with galactocentric distance in the course of Galactic chemical evolution. The evolving metallicity of the ISM will affect the physical and chemical properties of the nebulae out of which planetary systems are formed. In particular, the solids-to-gas ratio of the nebulae is expected to scale with the local metallicity. The solid-to-gas ratio is a key parameter in models of planet formation because it governs the rate of dust settling and coagulation in the protoplanetary disk. Typical values of the *solids-to-gas mass ratio* (R) commonly adopted for the solar nebula are $\mathsf{R} \cong 0.034$ for the rocky solids at ~1 AU and $\mathsf{R} \cong 0.1$ for the icy solids at ~10 AU (Weidenschilling 1980). However, if the solid-to-gas ratio scales with the metallicity, one should adopt lower values of R in modeling metal-poor proto-planetary nebulae typical of the early Galaxy. We show below that R seems indeed to decrease in nebulae observed in their early stages of evolution.

The dust-to-gas ratio is usually estimated by dividing the dust extinction of background light, A_V, by the line-of-sight column density of HI atoms, N(HI). The extinction per hydrogen atom, A_V/N(HI), increases with the interstellar metallicity in local galaxies (Issa et al. 1990) and in distant ones (Vladilo et al. 2006). The dust-to-gas mass ratio R is expected to follow a similar trend. However, the conversion of A_V/N(HI) into R requires the adoption of a dust grain model. A direct estimate of R can instead be derived from the expression

$$\mathsf{R} = [\, \Sigma_i \; f_i \, (X_i/Fe) \, A_i \,] \, / \, [\, \Sigma_i \, (1- f_i) \, (X_i/Fe) \, A_i] \quad , \qquad (1)$$

where the summatories are extended to the most abundant astrophysical elements; f_i is the *number fraction of each element in solid phase*, A_i the atomic mass, and (X_i/Fe) the abundance by number relative to iron, here adopted as a reference element. As an example, R can be estimated in this way in nearby clouds, where the fractions f_i can be obtained from measurements of interstellar depletions (Vladilo 2002) and the abundance pattern is known because $(X_i/Fe) = (X_i/Fe)_{SUN}$.

For the purpose of the present investigation we use Eq. (1) to estimate the interstellar dust-to-gas ratio in galaxies located at large cosmological distances along the line of sight to background quasars. The interstellar clouds of these galaxies produce a system of absorption lines in the quasar spectrum. The quasar absorption systems originated in foreground galaxies show a very strong HI Ly α absorption and are called damped Ly α (DLA) systems (Wolfe et al. 1986). The spectral lines of DLA systems are redshifted as a result of the

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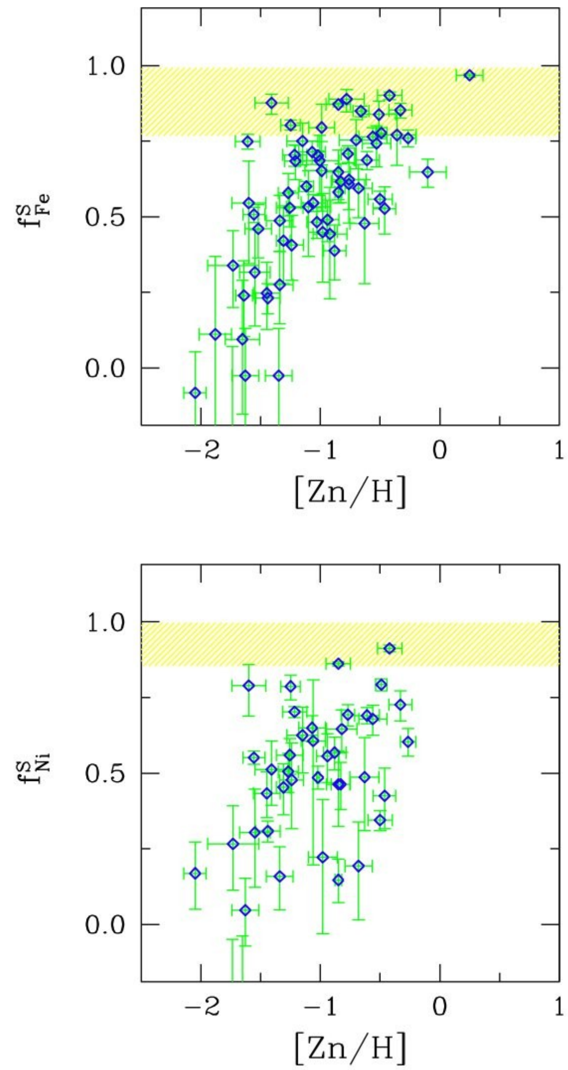

Figure 1: Dust fractions fi of refractory elements in DLA systems plotted versus metallicity M = [Zn/H]. Zinc is used as the reference element for interstellar metallicity since it is virtually undepleted into dust grains. Top: Iron dust fraction. Bottom: Nickel dust fraction. Yellow strips: typical range of dust fractions measured in present-day interstellar clouds of the Milky Way.

cosmological expansion of the Universe. The redshift z of DLA systems can be measured and converted to look-back time (time before the present) with great accuracy. When $z >$ 2, as in most DLA systems currently known, the look-back time is larger than ~10 Gyr. Considering that a galaxy like the Milky Way was formed less than 12 Gyr ago, this means that DLA galaxies are generally observed in the very early stages of their evolution.

The dust fractions f_i that appear in Eq. (1) can be estimated in DLA systems by comparing the abundances of refractory elements, such as Fe and Ni, with the abundance of a volatile element not incorporated in dust, such as Zn (Vladilo 2004). In Fig. 2 we show an updated collection of measurements of dust fraction of iron and nickel in DLA systems. One can see that the dust fractions f_{Fe} and f_{Ni} decrease at lower metallicities, with a drop down to about 50% of their typical interstellar values (yellow strips in the figure) at $M \sim -1.5$ dex.

These results suggest that also the dust-to-gas mass ratio R will decrease at low metallicities, with a drop at $M \sim -1.5$ dex, at least for rocky solids composed of refractory elements. The paucity of dust below this threshold may be the result of a reduced efficiency of the dust formation mechanisms in supernovae and stellar winds at very low metallicity (Todini & Ferrara, 2001; Ferrarotti & Gail, 2003). Also the metal-poor interstellar clouds of the young Milky Way, even if not directly observable, should have been characterized by a low value of R. This effect must have affected the probability of planet formation in the early stages of galactic chemical evolution.

1.2 Implications for planet formation probability

Proto-planetary disks form from the sedimentation of the left-over material of the parent interstellar nebula which gives birth to the central star. The dust of the nebula accumulates in the midplane of the disk and, according to accretion theories, leads to the formation of planetesimals (Lissauer 1993). The quantity of dust present in the nebula prior to the formation of the central star will affect the efficiency of planetesimal (and planet) formation. For conditions typical of the solar nebula, *e*-folding sedimentation times can easily be as high as $\sim 10^6$ years for 1 μm grains, and several *e*-folding times are required to produce a thin layer in which the dust and gas density are comparable, a minimum requirement for planetesimal formation (Lissauer 1993). To reduce these times one needs to invoke collisional growth of pre-existing grains during their descent to the midplane of the disk (Weidenschilling 1980). The results of the previous section suggest that pre-existing dust grains could have been very scarce at $M < -1.5$ dex. The scarcity of pre-existing dust grains could have delayed collisional growth and made the build-up of the critical disk density for planetesimal formation impossible within the life time of the disk. The typical life times of circumstellar disks is in the order of a few 10^6 years, with only a small fractio still present at $\sim 10^7$ years (Briceño et al. 2007).

Also the *size* of the dust grains, in addition to the dust-to-gas ratio, can affect the time scale of sedimentation of the solids in the disk. Low-metallicity interstellar clouds apparently have a grain size distribution enhanced at lower sizes. Evidence for this is present in the SMC-type extinction curve, generally associated with metal-poor clouds (see Vladilo et al. 2006 and refs. therein), which shows a sharp UV rise, typical

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of small grains. Small grains are strongly coupled to the turbulence in the gas and remain suspended in the midplane making the sedimentation process inefficient. Again, if the time scale of sedimentation is too large, the probability of forming planets before the disk is photoevaporated will decrease.

Finally, it is worth noticing that photoevaporation is more efficient at low metallicity, when the dust-to-gas ratio decreases, due to reduced self-shielding of the nebula from the UV radiation from the protostar.

1.3 A metallicity threshold for planet formation

The arguments discussed in the previous paragraph suggest a scenario in which the quantity and type of dust in low-metallicity proto-planetary nebulae may yield sedimentation times longer than the time scale for photoevaporation of the disk. In this scenario planet formation via accretion of rocky planetesimals would be inhibited. In order to reduce the sedimentation time, a minimum fraction of refractory elements must be in dust form. If we require $f_{Fe} > 0.5$ to keep the sedimentation process sufficiently fast, we derive a metallicity threshold $M > -1.5$ dex from the trend of f_{Fe} versus metallicity shown in Fig. 2. Below this threshold, which should be interpreted in a statistical sense, we argue that the protoplanetary disk would be photoevaporated before rocky planetesimals can be accreted. These arguments do not prevent, in principle, the formation of planets via gravitational instability of the gas. However, the formation of terrestrial-like planets would be inhibited.

The validity of the metallicity threshold proposed above can be tested by searches for extrasolar planets around metal-poor stars. Searches based on the doppler shift technique have not yet explored the metallicity range $M < -0.6$ dex. On the other hand, searches in crowded stellar fields based on the transit method are starting to provide results for metal-poor stars. So far, no planets have been detected in the metal-poor globular clusters 47 Tuc (Weldrake et al. 2005) and ω Cen (Weldrake, Sackett & Bridges, 2008), which cover a range of metallicities down to $M = -1.7$ dex. A planet detected in the globular cluster M4 ($M = -1.2$ dex) has probably been formed via gravitational instability triggered by a passing star (Beer, King & Pringle, 2004). Therefore, the available observational evidence does not provide examples that contraddict the above sketched scenario. Until a refined treatment of the probability of planet formation at low metallicity will not be available, we plan to use the threshold $M < -1.5$ dex to evidentiate zones with negligible probability of terrestrial planet formation in the metallicity maps of our Galactic simulations.

2. Simulating a Galaxy

2.1 The Galactic Habitable Zone

Obviously, the first request for complex life to exist is the existence of planets, which is possibly connected with the metallicity of the parent interstellar nebula, as discussed above.

Other parameters can however play a fundamental role. Lineweaver, Fenner & Gibson (2004) performed a study of the interplay among metallicities, stellar ages and what they called "supernova danger factor", that is the probability that complex life does not survive to the radiations (cosmic rays, gamma rays and X-rays) produced by the explosion of a nearby massive star (Clark, McCrea & Stephenson 1977). Such a danger factor has however large uncertainties (Scalo & Wheeler, 2002) and any attempt to model it should be regarded with caution.

Lineweaver, Fenner & Gibson used an analytical model for inferring the evolution of the pertinent parameters in the Milky Way. They normalized their model to the values observed for the solar neighbourhood and find that an annulus between 7 and 9 kpc from the galactic center matched their definition for the GHZ. Their model however had no spatial information, apart from the galactocentric distance, and they simply imposed two subsequent episodes of gas infall to account for the formation of the bulge and of the disk of the Galaxy.

2.2 The formation and evolution of a disk galaxy in a cosmological enviroment

In the last years, however, a huge effort has been made to understand the formation and the evolution of disk galaxies, like the Milky Way, in the context of our cosmological standard model. In such a model small density perturbations in an originally very uniform Universe grow via gravitational instability to give rise to all the complex structures which we can see today, from galaxies to clusters of galaxies. To reconcile the extreme uniformity we observe in the Cosmic Microwave Background Radiation (CMBR) with the large disomogeneities we see today, the model of structure formation introduces the hypothesis of the *dark matter (DM)*, a type of matter which does not shine and interact with the normal matter only with its gravity. To justify the amount of structures we observe in the local Universe, dark matter must be abundant; its exact amount can be inferred from the analysis of the CMBR combined with other observations, concerning e.g. the distant supernovae. From such an analysis, the matter in the Universe should be composed by 5/6 of dark matter.

Dark matter has been extensively studied using computer simulations. Models of structure formation based on it proved very succesfull in statistically describing the observed properties of the Universe and a number of observational

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hints are nowaday pointing towards its existance.

At first, cosmological numerical simulations only included the gravitational evolution of the dark matter distribution; now they also follow the evolution of the gaseous content of the Universe, by integrating its equation of motion (the Euler equations) and also by including several astrophysical processes as radiative cooling of the gas, star formation and energy feedback given by the explosion of massive stars as supernovae. Numerical simulations gave us some well estabilished conclusion: the formation and evolution of galaxies is linked with that of their *dark matter halo,* which has much more mass than the visible one. Dark matter haloes form first and the gas falls into them, cools down and forms stars and galaxies.

However, on the one hand, direct numerical cosmological simulations of the formation and evolution of disk galaxies still suffer of a number of technical problems mainly due to limitations in computer power. On the other hand, it is possible to simulate an isolated galaxy with high resolution; but doing so, the imprint of the cosmological enviroment on its evolution is lost.

2.3 Simulating an isolated galaxy in a cosmological fashion

We set up a new method for studying the evolution of an isolated disk galaxy in a cosmological context. We run low-resolution dark-matter only cosmological numerical simulations of a portion of our Universe having a side of 50 Mpc. inside such a simulated volume, we detected dark matter haloes which could host a disk galaxy. We considered parameters such as mass, angular momentum and accretion history of the haloes to determine if they are suitable to host a disk galaxy.

After identifying our candidate DM halo, we measured its accretion history (the way in which it accretes its mass as a function of time) and his concentration (a dynamical parameter characterizing the mass distribution inside the halo).

We then run isolated numerical simulations in which a gravitational potential, evolves in time according to the mass accretion history and to the evolution of the concentration of our chosen DM halo. We put a given amount of gas mass in hydrostatic equilibrium with the initial potential, gave it the same specific angular momentum of the DM halo, and let it radiatively cool, settle in a disk and form stars. The gas mass inside the halo grows with the same law we used for the DM gravitational potential.

We used the Tree+SPH N-Body code GADGET-2 (Springel 2005). In this code, the gravitational evolution of DM and gas distribution is followed via an N-Body technique, while the hydrodynamical forces are considered using an SPH technique. The code also follows the radiative cooling of the gas and has a well tested prescription for the star formation. We implemented in it the evolution of an external potential as described above. Tornatore et al. (2007) implemented in the same code a chemical evolution model, which will allow us to follow the enrichment of the interstellar gas for various chemical elements due to explosions of supernovae of type I and IIa.

Fig. 2 shows the result of a test simulation performed with this method. Here a gas particle has a mass of ~10^6 solar masses and a formed star particle has ¼ of its mass. The final disk, after 11.35 Gyr of evolution, contains ~230,000 star particle for a total mass of ~5.8 10^{10} solar masses, very similar to the Mily Way mass. The 8 panels show face-on and edge-on projections of star formation rates, stellar ages, stellar density and stellar metallicity (we didn't use the full Tornatore model for this test, but a simplified one), color-coded logarithmically from smaller (dark blue) to higher (white) values.

Our test run proves qualitatively able to reproduce a realistic

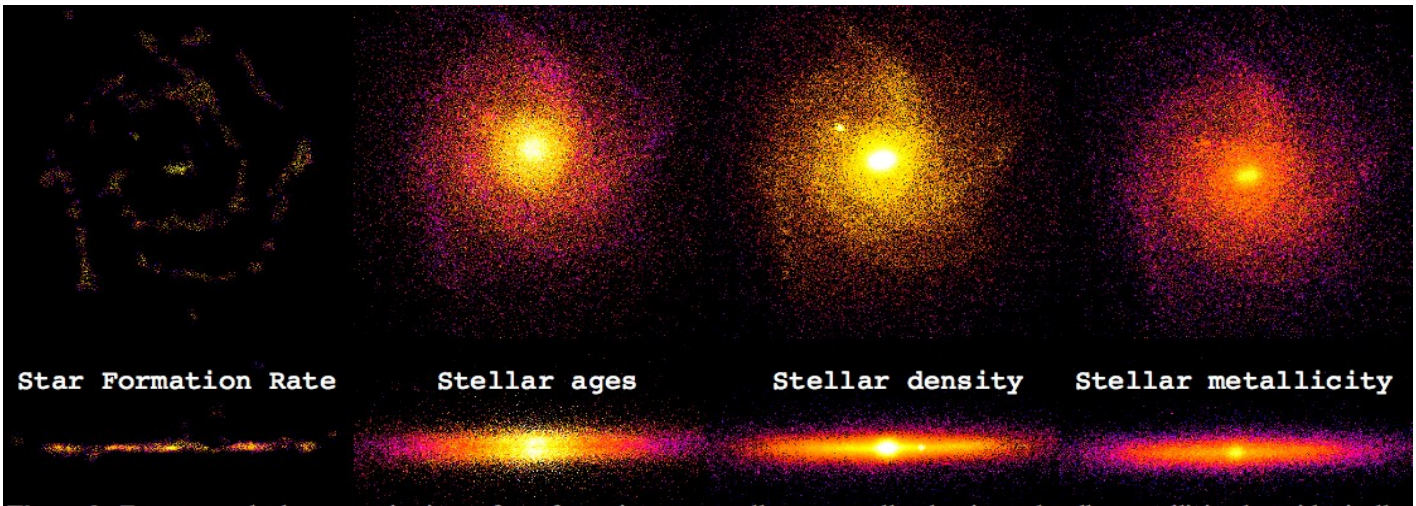

Figure 2. Face-on and edge-on projections of star formation rates, stellar ages, stellar density and stellar metallicity, logarithmically color-coded from lower (dark blue) to higher (white) values, for the simulation described in text after 8 Gyr of evolution.

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disk Galaxy, with spiral arms in which the bulk of star formation takes place, a metallicity gradient from the center to the outskirts, and older stars dwelling in the center while younger ones lies in outer regions of the disk.

Our method has the advantage that resolution can be greatly improved, while keeping the computing time relatively low. In our final runs, we will produce detailed metallicity maps at different times, together with density and star formation maps. The latters give a precise distribution of supernovae II and Ia explosions, in space and time, while the former can be used to estimate the probability distribution of planetary systems.

Put together, we will use such informations to determine possible Galactic Habitable zone of Milky Way-like galaxies, also varying the prescriptions which link astropysical observables to the probability of having complex life. Our most optimistic aim is to predict where, in a galaxy like ours, complex life could be most probably found.

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