Chapter 1

The multiplicity of timescales — challenges in modeling astrophysical systems

Abstract

Timescales in astronomy spans comprise the largest range of any scientific field. This is both a blessing and a curse.

1.1 Introduction

NO SCIENTIFIC FIELD deals with a longer span of time scales than astrophysics. From explosion mechanisms in dying stars and oscillations of neutron stars, to cosmic structure formation and the age of the Universe itself, more than twenty orders of magnitude prevail. Counting Big Bang physics as "astrophysics" doubles or even triples this amount[1]. However, while this enormous dynamic range can be challenging to model under one umbrella, it may also be an advantage: Many characteristic features of various astrophysical phenomena can be understood simply by comparing relevant physical time scales.

While the short end of this range of time scales is in many cases observable, an inherent problem in astronomy is that many processes occur on time scales much longer than a human life, or even a human civilization. How, then, may we say anything about how stars form, how galaxies evolve, or which phases the Universe has gone through?

Several approaches exist to answering this question: Observationally, while we cannot wait to witness the evolution of any given galaxy — which to us puny humans seems frozen in time — we are lucky to live in a universe where the

[1] The age of the Universe is $\sim 10^{61}$ Planck times!

speed of light is finite, but fast. As we peer deeper into the cosmos, we probe earlier and earlier epochs. Observing large samples of galaxies throughout cosmic history then allows us to study their properties in a statistical sense — properties such as their star formation rates, build-up of heavy elements, and changes in morphology.

On the theoretical side, as in many other fields of science we make use of *models*. Models that predict the evolution of these various physical properties, while being consistent with already known physical properties. Models can be analytical, numerical, or a mixture thereof; the so-called semi-analytical models. In this chiefly theoretical review I will discuss two extrema of astrophysical time scales; first the formation and evolution of galaxies, and subsequently zooming into the micro-scales of galaxies, the atoms.

1.2 Times scales in the evolution of galaxies

One of the revelations of the 1970s was that, in contrast to the prevailing picture at the time, galaxies do not form from huge, "monolithically collapsing" clouds that later fragment to stars (**?**). Rather, it seems to be the other way round, with small structures forming first, later building up to larger structures in a hierarchical manner. A brief outline of the physical processes leading to a galaxy can be summarized as follows:

1.2.1 Galaxy formation

In the early, expanding Universe, sufficiently large overdensities are able to withstand and detach themselves from this expansion, turn over, and collapse. With more than five times as much dark matter as baryonic matter, the dynamics are initially dominated by the former. Eventually the cloud will *virialize* — astronomers' term for reaching a dynamical equilibrium — and come to a halt. Gas, which unlike the collisionless dark matter is able to cool and fragment further, condenses in the center of more extended dark matter halos.

In the very center, supermassive black holes form which accrete mass, ejecting excess energy as so-called *active galactic nuclei* (AGN). Meanwhile, dying stars inject not only energy but also heavy elements (in astronomy, everything heavier than helium is collectively called "metals"). With time, the interstellar medium (ISM) is therefore enriched with metals, part of which condenses to dust.

Thermal and kinetic feedback from stars and AGN drive strong winds which may exceed the galaxy's escape velocity, enriching also the intergalactic medium (IGM) with metals. Star formation typically declines after an initial starburst, but may be sustained by continuous accretion of new material from the IGM, while new starbursts may be initiated by collisions with other galaxies, a process known as *merging*. Galactic winds, merging, and gas depletion is also responsible for some galaxies ceasing to form new stars.

Which processes dominate will determine the nature of the galaxy, in particular its morphology — will it end up as a disky spiral galaxy, a featureless elliptical galaxy, or something else?

1.2.2 Using time scales to predict galactic properties

All structure in the Universe is, ultimately, born out out primordial fluctuations in the density field which can be described by an almost scale-free power spectrum. In other words, the Universe doesn't have a preferred scale, and neither does gravity (there are no characteristic masses in the Einstein equations). We might therefore expect structure to form in equal ratios between masses, that is if there are α times as many structures with mass M.