Simulating the formation of supermassive black hole binaries

Marco Bianchi
University of Milano-Bicocca, Physics Department, Astrophysics and Space Physics master degree
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ABSTRACT

The Cocoon Nebula (IC 5146) is an HII region embedded within the Barnard 168 absorption nebula, making it a prime target for studying dust extinction. We obtained photometric images of IC 5146 using Hα and Hβ filters and analyzed the Balmer decrement to create a two-dimensional map of the color excess E(B-V), which serves as a proxy for dust column density. Our results indicate a median E(B-V) of $\approx 0.461 \pm 0.008$ across the nebula, with a standard deviation of ≈ 0.34. A comparison with previous spectroscopic studies reveals a discrepancy in E(B-V) estimates, which we attribute to methodological differences in spatial sampling.

Furthermore, given the nebula's nearly spherical morphology and its ionization by a single B0.5V-type star (BD+46 3474), we tested the Strömgren sphere model. By incorporating literature values for electron density and temperature, as well as for the radius and temperature of BD+46 3474, we derived a Strömgren radius of ≈ 1.14 pc, which is broadly consistent with the observed nebular size. However, uncertainties in the nebula's distance and simplifying assumptions in the Strömgren model highlight the need for more detailed modeling.

1 INTRODUCTION

It is a well-established fact that most galaxies host a massive black hole (MBH) at their center, with masses ranging from a few million to several billion solar masses. In the latter case, these are referred to as supermassive black holes (SMBHs). On the other hand, galactic mergers are expected to be frequent events in the Universe, and indeed we observe many galaxies in various stages of the merging process. This raises the question of what happens to MBHs during these mergers. The most likely outcome is the formation of a MBH binary at the center of the newly formed galaxy. The process leading to the formation and the evolution of such a bound state is complex and involves several stages, which were originally outlined by Begelman et al. (1980).

1.1 Dynamical friction

In this work, we focus on the process that causes the MBHs to sink towards the core of the merger remnant, a mechanism known as **dynamical friction**. The main idea is that a massive object moving through a stellar system will transfer energy and angular momentum to the surrounding stars, slowing down and thus spiraling inward, toward the center of mass of the system. The object may gain speed as it moves into a region with deeper gravitational potential, which does not contradic the previous statement, since the total orbital energy is still decreasing. The mathematical formalization of dynamical friction was first proposed by Chandrasekhar (1943), and it is based on the assumption that the stellar background is homogeneous and isotropic. In particular, the perturber is subject to a deceleration given by the following equation:

$$\frac{d\vec{v}_M}{dt} = -16\pi^2 G^2 m\,(m+M)\ln\Lambda \left[\int_0^{v_M} f(v_m)\, v_m^2\, dv_m\right] \frac{\vec{v}_M}{v_M^3}, \quad (1)$$

where $\ln\Lambda$ is the Coulomb logarithm (which depends on the maximum and minimum impact parameters of the interaction), m is the mass of the background particles, M is the mass of the perturber, and $f(v_m)$ is the distribution function of the background particles. It can be shown that dynamical friction is maximally efficient when $v_M \simeq v_m$, which is the typical case during the inspiral, and becomes negligible for $v_M \ll v_m$ or $v_M \gg v_m$.

Once the MBHs have sunk to the center of the merger remnant and their relative separation is such that the dynamics of one is dominated by the gravitational pull of the other, then they form a bound state. The critical separation can be approximated by the **influence radius**, i.e., the distance at which the gravitational potential of the MBH is comparable to the kinetic energy of the surrounding stars:

$$r_{\rm inf} = \frac{GM}{\sigma^2} \approx 1 \left(\frac{M}{10^6 M_\odot}\right)\left(\frac{\sigma}{65\rm km/s}\right)^{-2} \rm pc, \quad (2)$$

where σ is the velocity dispersion of the stars surrounding the MBH.

The formation of the binary causes a sudden change in the velocities of the MBHs with respect to the surrounding stars, making the dynamical friction process inefficient. The next step is to understand whether there exist other processes capable of reducing the binary separation, eventually leading to coalescence. It is well known that binaries of compact objects lose energy and angular momentum through the emission of gravitational waves, shrinking the orbit. However, this process is only efficient when the binary separation is already very small, of the order of a few milliparsecs. We therefore need to identify a mechanism that can efficiently reduce the binary separation from a few parsecs to milliparsecs. This is the so-called **"final-parsec problem"**, which has been the subject of extensive research in the past few decades. The most promising solution to this problem is **stellar hardening**, which is the process by which stars undergo three-body interactions with the binary, taking away energy and angular momentum.

1.2 Modeling galactic bulges

2 DISTRIBUTING PARTICLES ACCORDING TO VARIOUS MODELS

2.1 Isothermal sphere

prova

2.2 King model

prova

2.3 Hernquist model

prova

3 SIMULATION

4 CONCLUSION

REFERENCES

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