Highlights on Spanish Astrophysics X, Proceedings of the XIII Scientific Meeting of the Spanish Astronomical Society held on July 16 – 20, 2018, in Salamanca, Spain. B. Montesinos, A. Asensio Ramos, F. Buitrago, R. Schödel, E. Villaver, S. Pérez-Hoyos, I. Ordóñez-Etxeberria (eds.), 2019

The role of viscosity and EUV/RX radiation in the dispersal of protoplanetary discs.

Juan C. Vallejo[1,2] **and Ana I. Gómez de Castro**[1,2]

[1] JCUVA, Joint Center for UV Astronomy, AEGORA research group,
Universidad Complutense de Madrid, 28040, Madrid, Spain
[2] Dpto. Física de la Tierra y Astrofísica, Fac. de CC. Físicas, Universidad Complutense de Madrid, 28040, Madrid, Spain.

Abstract

The EUV and X-ray radiation of host stars in protoplanetary discs produce photoevaporative processes that seem to play an important role in their evolutionary time-scales. The viscosity of the discs is a fundamental parameter when modeling these discs using the α-prescription. Unfortunately, there is no single accepted value for this viscosity, and the results are very dependant on that value. Our work has implemented a grid of simple $1D$ models in which the value of the viscosity is systematically changed. This allows to analyse how different diagnostic diagrams of observable quantities evolve as the α value changes.

1 Introduction

The protoplanetary discs are the natural scenario for planet formation processes. They provide the material from which planets form in between the accretion and post-accretion phases of the disc. Understanding their evolution and the mechanisms and time-scales by which the disc is eventually dispersed is a key issue in planet formation and life emergence theories.

Hence, the importance of analysing the mechanisms leading to changes in the accretion processes that may modify the disc's chemistry, the dust-to-gas ratio and can starve the gas reservoir available for planet formation. As the mass accretes onto star, the conservation of momentum implies that the disc spreads out, the accretion decreases with time and the radius increases with time. Internal viscous transport and magnetised winds are main candidates to explain this transport. There are other mechanisms, such as planet formation, dust growth and encounters with other stars. However, it is not clear how these mechanisms can produce global changes from 0.1au to 100au in the disc properties [5].

2 The viscous discs and the α prescription

The circumstellar optically thick discs are typically observed at ages of 1Myr, but such discs seem to have disappeared at ages around 10Myr. Therefore, transitional discs must be relatively short-lived, with transition times from primordial to discsless of roughly 10 per cent of the disc total lifetime [2]. The standard explanation to the observed spectral characteristics and the so-called "two-timescale behaviour" relies in a mass depletion mechanism, that produces a hole in the dust of the inner regions of the disc, and clearing processes quickly proceeding from the inside out once this gap opens.

The viscous evolution is a widely used model for explaining the transition from disc-possessing to discless status. The molecular viscosity of the gas is too small to produce significant evolution, but the viscous approach is quite common when ones interprets the viscosity as the outcome of a turbulent process. The so-called standard model, or α-model, for viscous accretion discs, was first formulated by Shakura and Sunyaev [11]. The original work relied on an optically thick accretion disc and a turbulent fluid described by a viscous stress tensor proportional to the total pressure. It can be shown that the kinematical viscosity can be written in this case as,

$$\nu(r) = \alpha c_s H(r), \tag{1}$$

where the $H(r)$ profile models the disc thickness, and the α parameter is a scaling factor of the friction between adjacent rings. Later on, this parameter turned into a "standard" dimensionless measure of viscosity, that conveniently hides the real viscosity mechanism, but somehow characterises its effectiveness. However, one must note that even within the same disc, the α value can have different values at different locations of the same disc, and even it can evolve with time.

There is a variety of mechanisms that can create these turbulent processes. The magnetorotational instability (MRI) has been a leading candidate for turbulence and angular momentum transport. However, the MRI can nonetheless be suppressed in non-ideal MHD [10], and there are other mechanisms to consider, such as outflows, hydrodynamical processes and gravitational instability, see [1] and references therein. Magnetic fields can be also of importance in momentum transport mechanisms and disc accretion may be primarily wind-driven with magnetised disc winds [3]. But, independently of the viscous mechanism, the α-parametrisation is still widely used as a way for hiding the details of the viscous transport mechanism. A value of $\alpha = 0.01$ was initially used because it provided evolutionary time-scales in line with known properties of discs [7]. Later on, values ranging from 0.1 to 0.001 were in use (for instance, [8]). Nowadays, even lower values like 10^{-4} can be found [6].

3 Internal photoevaporation winds and viscosity

The observed two-timescale behavior in α-discs implies an efficient mass removal mechanism. The photoevaporation processes were firstly described in [4] as a convenient way to shutdown the mass accretion and trigger the disc dispersion. We briefly describe this model here. When

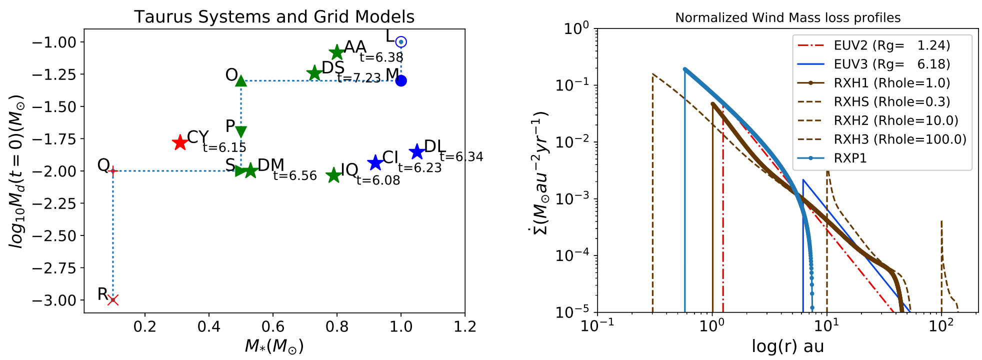

Figure 1: (Left) Some representative systems in the Taurus star forming region and the selected grid of discs models in the $M_* - M_d$ plane. The disc masses are the initial values. Hence, as the age of the discs increases, the initial points will move downwards in the diagram. In a very rough fashion, bluer Taurus stars means larger values for the mass of the host star. (Right) Normalised photoevaporative wind mass losses for diferent EUV and XEUV cases. The EUV winds have more localised wind losses, and the disc is hardly depleted at large radii. Conversely, XEUV winds are stronger and more extended. However, the X-ray winds strongly depend on the evolving geometry of the disc, mainly depending on the absence (RXP1 curve) or presence and size of a hole inside it (RXH1-3 curves).

the thermal velocity exceeds the local escape velocity, the surface layer gets unbound and evaporates, and a thermal wind with a speed comparable to the speed of sound (slow wind) takes away the disc gas. The calculation of the accreted mass can be done by computing the surface density $\Sigma(r,t)$ based on basic laws of mass and momentum conservation, as follows,

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}[r^{1/2}\frac{\partial}{\partial r}(\nu \Sigma r^{1/2})] - \dot{\Sigma}_w, \qquad (2)$$

where Σ_w denotes the mass loss by a given photoevaporative wind, functionally equivalent to have a sink for the mass.

We aim to analyse the interplay of the viscosity and photoevaporation processes, exploring the impact of the α values in the evolutionary time scales of different disc systems. For doing so, we have created a grid of models covering a variety of star masses and disc masses, for systematically changing the viscosity value. This grid is seen in the left panel of Fig. 1. The simple 1D model described by Eq. 2 allows to add different sink terms, corresponding to different thermal winds, to every modeled viscosity value. Therefore, we can solve the viscous evolution equation and compare the results got using EUV pure winds or EUV plus X-ray (XEUV) winds, with some real reference Taurus discs. The normalised winds mass profiles we have used are seen in the right panel of Fig. 1.

The final goal of our work is to crosscheck the results from our simulations with real systems, aiming to see how different viscosities affect typical diagnostic diagrams based on observable quantities. As a first approach, we have selected systems in the Taurus star-forming region because this is one of the nearest ($\approx$ 140 pc) and best-studied regions. Here,

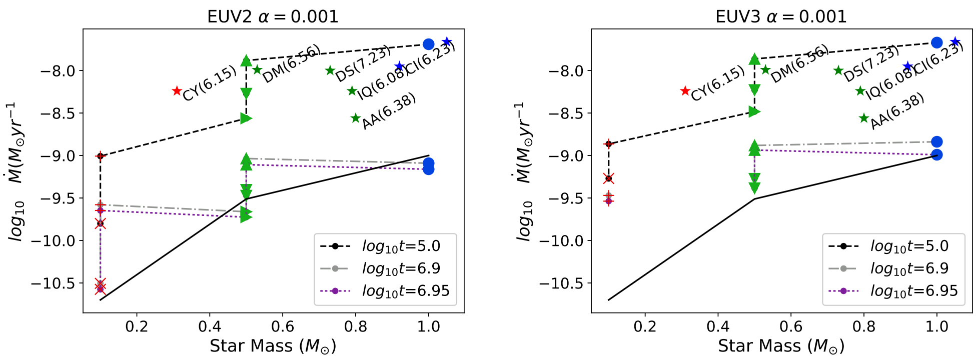

Figure 2: The role of the EUV strength in the evolution of the isochrones $\dot{M} - M_*$. (Left) The weakest EUV2 wind. (Right) The strongest EUV3 wind. As the age increases, the index of the power law relationship decreases. This decrease is faster as the viscosity and the strength of the EUV winds is larger. The Taurus systems and their ages are plotted for reference.

one can find loosely associated but rather isolated molecular cores. Hence, the influence of outflows, jets, or gravitational effects is minimised in this region.

3.1 EUV photoevaporation

The first photoevaporative process being added to the viscous evolution of a disc was the EUV photoevaporation [4]. The EUV computations are not quite complex, because the temperature of photoionised gas can be considered nearly constant $T \approx 10^4$K and one can compute mass losses based on a Stromgen criterion. However, when modelling these winds, we have seen the huge impact of some parameters in the results. Mainly, the gravitational radius, or distance at which the thermal energy is equal to the mechanical energy of a parcel of gas in keplerian rotation around the star. The strength of the wind heavily depends on both this radius and the EUV flux of the host star, and both values must be considered [12].

We have plotted diagnostic diagrams, such as the isochrones $\dot{M} - M_*$. The Figure 2 shows their evolution for two values of the viscosity. In a viscous-only disc, as the age increases, the power law relationship index decreases, faster as the viscosity is larger. When an EUV wind is added, this evolution is faster, but its very dependant on the gravitational radius. For the largest viscosities and stellar masses, the slope is made negative very quickly. For smaller viscosities, the change is no so fast, but still very noticeably. When comparing the rate of evolution of systems with the same stellar mass, the role played by the disc mass becomes very relevant, because the differences between these models grow with time faster than when the wind was not present.

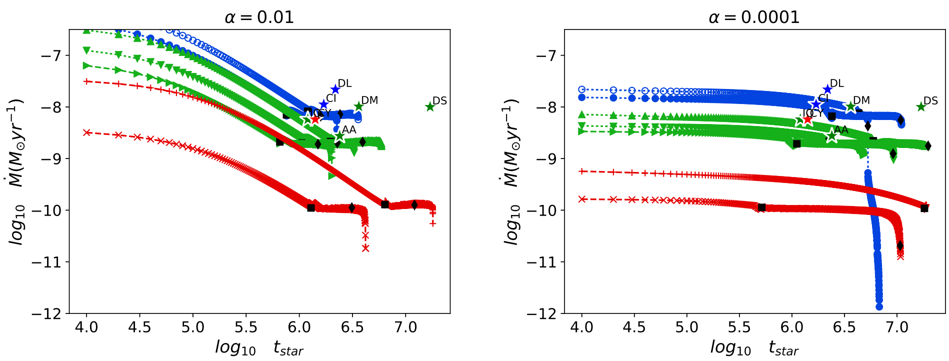

Figure 3: The role of the viscosity in the evolution of the mass accretion rate in the XEUV winds case. Same color and marker shape means same stellar mass. The bluer the color, the larger the mass. With the larger viscosities, the rate of accreted mass decreases faster. Black squares mark the hole opening time, black diamonds mark when the hole size is 100a.u.

3.2 XEUV photoevaporation

The physics of X-ray heating is by far more complex than the EUV processes described before. They rely in the X-ray photons in the $0.1 - 10$ KeV range that can tear off the electrons from the internal shells of metals. To treat the photoevaporative X-wind in the simple $1D$ viscous evolution model described by Eq. 2, we will follow the same approach taken in [6]. We will write a mass sink term $\dot{\Sigma}_{wind}$ based on the numerical fit to the simulations done by [9], where both EUV and X-ray contributions were introduced (noteworthy, the EUV contribution can be neglected when the X-ray radiation is present, even for the strongest UEV fields and the weakest X-ray fields). This model has two different epochs, hence two wind profiles delimited by the presence or not of a hole in the disc. There is an initial, primordial phase, that lasts until a gap opens. Once this gap is present, the wind fully clears the disc at given distances as gap grows and the inner edge of the outer disc is exposed directly to stellar irradiation.

The mass loss rate $\dot{M}$ is a fundamental observational parameter in the analyses of protoplanetary discs. This quantity is obtained by integrating the surface density $\dot{\Sigma}(r)$ at every instant during the numerical integration of the model. In general, as the viscosity decreases, the transport of mass, thus the evolution towards final state, is slower.

The Figure 3 shows this evolution for two values of the viscosity. We have also overlaid the representative Taurus systems. Obviously, Taurus ages, are subject ot experimental uncertainties. However, the main goal is to check the impact of the viscosity on the evolution of the disc, and these figures already show how one can match the theoretical and observational points by increasing the initial accretion rates $\dot{M}(t = 0)$. But the required increase seems to be huge. Therefore, a better alternative seems to consider lower values for the viscosities.

4 Conclusions and on going work

Simple 1D models based on the α-disc prescription, with α hiding a specific viscosity mechanism, can complement complex hydrodynamical simulations due to their simplicity in interpreting results. However, one should fully understand the limitations when handling this simplicity and modeling the discs with a single unique value. More work is needed for constraining the photoevaporative models with different observational parameters. The age of the systems and the disc masses must be improved for making these diagnostic diagrams more useful when comparing the results from simulations with real data. Future UV missions are required for providing further data in this area, and will help for improving these comparisons.

Acknowledgments

Juan C. Vallejo and Ana I. Gómez de Castro thank the Spanish Ministry of Economy, Industry and Competitiveness for grants ESP2014-54243-R and ESP2015-68908-R.

References

[1] Armitage, P.J. 2015, arXiv:1509.06382

[2] Anderson, K.R., Adams, F.C. and Calvet, N. 2013, ApJ, 774, 9

[3] Bai., X. 2016, ApJ, 821, 80

[4] Clarke, C.J., Gendrin, A. and Sotomayor, M. 2001, MNRAS, 328, 485

[5] Dullemond C. P., Dominik C. 2005, A&A, 434, 971

[6] Ercolano, B., Jennings, J., Rosotti, G., Birnstiel, T. 2017, MNRAS, 472, 411

[7] Hartmann L., Calvet, N., Gullbring, E., D'Alessio, P. 1998, ApJ, 495, 385

[8] Jones, M.G., Pringle, J.E., Alexander, R.D. 2012, MNRAS, 419, 925

[9] Owen, J.E., Clarke, C.J. and Ercolano, B., 2012, MNRAS, 422, 1880

[10] Riols, A., Lesur, G. 2018, A&A, 617, A117

[11] Shakura, N.I., Sundayev, R.A. 1973, A&A, 24, 337

[12] Vallejo, J.C., Gómez de Castro, A.I. 2018, APSS, 363, 246