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From protostellar to pre-main-sequence evolution

F. D'Antona

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Roma, Via di Frascati, I-00040
Monte Porzio Catone, Italy, e-mail: `franca.dantona@gmail.com`

Abstract. I summarize the status of pre-main-sequence evolutionary tracks starting from the first steps dating back to the concept of Hayashi track. Understanding of the dynamical protostellar phase in the vision of Palla & Stahler, who introduced the concept of the deuterium burning thermostat and of stellar birthline, provided for a long time a link between the dynamical and hydrostatic evolution. Disk accretion however changed considerably the view, but re-introducing some ambiguities which must still be solved. The limitations and uncertainties in the mass and age determination from models for young stellar objects are summarized, but the burning of light elements is still a powerful observational signature.

Key words. Stars: abundances – Stars: Population II – Galaxy: globular clusters

1. Introduction

In the sixties of the twentieth century still researchers had no clear idea of the protostellar phase, and the first important approach to pre-main-sequence evolution was set in the work by Hayashi (1966), describing the hydrostatic contraction from very high radii and luminosity of the molecular cloud. The objects were fully convective, and therefore the temperature gradient in their structure was the maximum possible gradient on a hydrostatic structure, so the "Hayashi tracks" defined the line, for each mass, limiting the minimum T$_{\rm eff}$ of models. It was soon clear that the high luminosity predicted by these evolutions were not existing in reality, as the young objects, for solar type stars, the T-Tauri, were one to two orders of magnitude less luminous.

The hydrostatic evolution is a simple contraction subject to the Virial theorem: in a first approximation (not valid at the lowest masses) half of the gravitational energy released is radiated, and half goes to increase the thermal energy. This relation defines the "characteristic lifetime" of a structure at luminosity L, sustained only by gravitational contraction (the Kelvin-Helmholtz timescale. Considering the T$_{\rm eff}$ approximately constant along the Hayashi track, it is easy to recover that the age of the star is proportional to the power –3/2 of the luminosity,

$$t \simeq 0.2 \left(\frac{M}{M_\odot}\right)^2 T_{\rm eff}^2 \left(\frac{L}{L_\odot}\right)^{-3/2} \ {\rm yr} \qquad (1)$$

from which it is easy to see that all perturbations to pure contraction (e.g. deuterium burning, or residual accretion from the protostellar disk) alter the youngest ages, but are easily forgot "in the end" (again, very low mass stars and brown dwarfs must be considered more carefully).

2. The hydrodynamical phase and the role of D-burning

The first attempts to describe the hydrodynamical phase of collapse of the protostellar cloud (Larson, 1969) showed a marked contrast with the Hayashi type evolution, for which several models were already available (e.g. Iben, 1965): the Herzsprung-Russell (HR) evolution was much more complicated! The most prominent problem, which is present also in the recent computations, is the following: "when", during the evolution of the protostar, can we say that the object becomes "visible" (in the optical, or at least at near-infrared wavelengths) so that we can set a boundary between *protostar* and *pre-main-sequence*?

This question received a satisfactory answer in the approach by Stahler and coworkers (Stahler et al., 1980a,b; Stahler, 1983; Stahler et al., 1986; Palla & Stahler, 1991, 1992, 1993) The main phase of proto-star evolution is characterized by accretion from the envelope onto the hydrostatic core, defining the Mass-Radius relation. In spherical synnetry, for $M \lesssim 1 M_\odot$, the most important event is the onset of deuterium-(D-) burning during the main accretion phase, because it halts the hydrostatic core contraction and induces full convection in the core. Thus, when the main accretion phase ends, the star appears on the track of its final mass *at the D-burning line (birthline)*. This simple model reconciles hydrostatic and dynamic evolution "where it matters", at the T-Tauri stage.

3. The role of pre-main sequence

Palla & Stahler's thermostat view is the way we can appreciate back the usefulness of standard evolutionary tracks for low mass stars: apart from a zero age problem – depending on the duration of the protostellar phase – standard evolution along the convective pre-main sequence is a reasonable approximation, following the D-burning stage. This means we can use standard tracks to date young populations (possibly not very young) if their component stars have finished the "rapid" protostellar accretion phase. Remembering that the thermal timescale will always become the dominant factor, for increasing ages the pre-main sequence age will become more and more well determined, in spite of the uncertainty in preceding evolution.

The birthline definition bears obvious uncertainties, which have been explored already in the works by Palla and Stahler. The mass–radius relation of the hydrostatic core depends on the D-abundance in the gas (Stahler, 1988), on the proto-stellar accretion rate, and on the boundary conditions (Palla & Stahler, 1992): are we in the presence of radial accretion (as implicit in one dimensional computation), so in this case the boundary condition is set by the shock region, or of disk accretion, so the boundary conditions are set at the photosphere?

4. Disk accretion

The existence of FU Ori outbursts (Herbig, 1977) and, mainly, of EXors with close repeated variability (Herbig, 1989) require the mediation of an accretion circumstellar disk. In fact it is possible that intermittent (disk) accretion is the way stars acquire the bulk of the mass, starting during the protostar phase (Vorobyov & Basu, 2005; Baraffe et al., 2009). Disk accretion alters protostellar evolution, and also the classical T-Tauri phase (CTTS) (Mercer-Smith et al., 1984; Hartmann et al., 1997). In principle, the result of models including disk accretion lead to a more uncertain definition of stellar 'zero age', and to spread of luminosity in coeval low mass stars (Baraffe et al., 2009).

Most of these models predict that the birthline is less luminous than the classic Palla–Stahler birthline (e.g. Vorobyov et al., 2017). The role of pre-main sequence evolution in such a case is considerably shaken. This result depends on several additional physical inputs and parameters entering the disk accretion description A critical factor is the fraction ξ of accretion energy acquired by the star

$$L_{add} = \xi G M_* \dot{M} / R_* \qquad (2)$$

that is, how 'cold' is accretion (e.g. Hartmann et al., 2016), and where the accretion energy is deposited. Most models computed so far

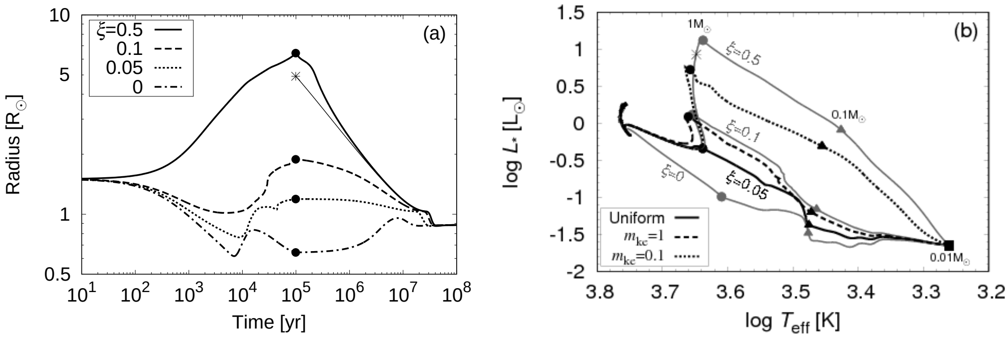

Fig. 1. From the work by Kunitomo et al. (2017), radius (left) and HR diagram evolution (right) of tracks starting from 0.01M$_\odot$ and accreting till 1M$_\odot$. The classical evolution is also shown, starting at the asterisk. Different injection energy efficiency (ξ) are assumed as labelled. In the HR diagram, for the case ξ=0.05, the difference between assuming that the injection energy is uniformly and instantaneously distributed (solid line), or is distributed non uniformly, following equation 3 in Kunitomo et al. (2017), either in the whole star ($m_{\rm ke}$=1), or in the outer 10% of the star ($m_{\rm ke}$=0.1). It is evident that the distribution of even a small quantity of injection energy plays a fundamental role.

follow the assumption by Baraffe & Chabrier (2010), that the accretion energy is instantaneously uniformly distributed into the whole star, accounting for an energy generation per gram $\epsilon_{add} = L_{add}/M_*$. However, Kunitomo et al. (2017) computed models in which, more realistically, the accretion energy is distributed linearly on an external mass layer of fixed mass (m_{ke}) (see Figure 1) showing that even the deposition of a small fraction of accretion energy in the outer layers leads to begin the pre-MS evolution at larger radii than in other disk accretion models, reconciling again disk accretion with standard evolution beginning at the D-burning birthline.

5. Mass and age determination of young stellar populations

Pre-MS models are badly needed to put constraints on the ages and masses of stars observed in young clusters and associations. The masses help us in defining the initial mass function, and the age spreads are needed to improve our understanding of star formation. I wish to remember here one important recent observational efforts, namely the Hubble Space Telescope Treasury Program of the Orion Nebular Cluster (P.I. M. Robberto), which is still providing a plethora of data, mainly on the low mass stars and brown dwarfs, and thus potentially on the low end of the stellar – substellar mass function (Da Rio et al., 2012), see Figure 2.

Computing standard pre-MS evolution is 'simple', so there has been a flourishing of evolutionary tracks in the 1990's, (e.g. D'Antona & Mazzitelli, 1994, 1997; Baraffe et al., 1998; Siess et al., 2000), but also in the next decades (Montalbán et al., 2004; Dotter et al., 2007; Tognelli et al., 2011; Baraffe et al., 2015). Being stars fully convective during the the Hayashi part of the evolution, the main requirement is to have a satisfactory description of the adiabatic gradient in regions of partial ionization (and thus, a good knowledge of the equation of state) and of the super-adiabatic gradient in the most external layers. Thus much of the effort was first focused on having reliable opacities for the regions of partial ionization, and a reliable equation of state, especially for the non ideal gas regions (high density – low temperature) necessary to compute the structure of low masses and brown dwarfs. The superadiabatic convection was approached mainly by the mixing length theory (MLT) description, in which the parameter α, the ratio of mixing length to pressure scale height, was

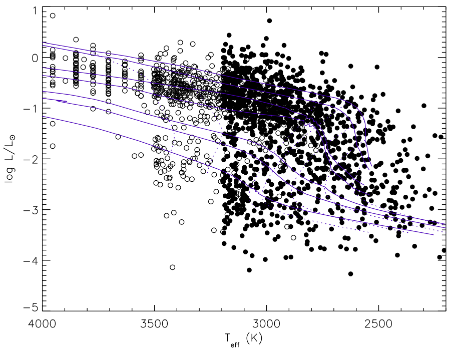

Fig. 2. Orion data (as displayed by Giulia Ubeira Gabellini et al., 2016) compared with the isochrone locations by D'Antona & Mazzitelli (1997).

generally fixed at the value able to reproduce the solar radius at the solar T$_{\rm eff}$. Obviously this value changed in the course of years, following the update of opacities and of solar element abundances determination. In our own models, my husband Italo Mazzitelli and I decided to rely both on the MLT and on the new description of convection by Canuto & Mazzitelli (1991) and Canuto et al. (1996) which was still a local model, but took into account the energy distribution of eddies – so it took the name of Full Spectrum Turbulence (FST) model. In addition, assuming as scale length the distance of the turbulent layer from the top/bottom of convection, the solar model requires only a small adjustment of secondary parameters to be fit. Remember that present-day values of the α_{MLT} to match the solar T$_{\rm eff}$ range between 1.7 and 1.9 times the pressure scale heigth, so the MLT real meaning is to provide an average gradient of the convective structure, and not a physical meaning.

The main improvement of these models, begun with the Baraffe et al. (1998) effort – but see later – was to introduce in the models more reliable boundary conditions (Hauschildt et al., 1999), taking into account that the atmospheric structure at T$_{\rm eff}\lesssim$4000 K, is affected by the presence of triatomic molecules, so that improved molecular line lists must be used for various atmospheric absorbers. Later on, the use of non-grey boundary conditions resulted particularly important for the coolest models (see the DUSTY and COND models by Allard et al. (2001). The spectra and spectrophotometric indices emerging from these new model atmospheres are also important to derive reliable T$_{\rm eff}$'s for the low temperature objects (Da Rio et al., 2012).

While the use of appropriate boundary conditions is mandatory, especially at masses M$\lesssim$0.4M$_\odot$, the differences for the masses M>0.4M$_\odot$ reach several hundreds of degrees and are all due to the different treatment of convection (see, e.g. Tognelli et al., 2011).

In particular, the Baraffe et al. (1998) models are the coolest, but note that this particular result *is not* due to the use of non-grey boundary conditions, but, again, to a particular use of MLT made in those models. In fact, they choose model atmospheres with α_{MLT}=0.5, and set the match with the interior integration at τ=100. So, convection was very *inefficient* for a large fraction of the stellar envelope, where the gradient was largely close to the radiative gradient, so that a lower surface T$_{\rm eff}$ would result from a given central temperature T$_{\rm c}$. Montalbán et al. (2004) showed that the the temperature gradient (and the resulting T$_{\rm eff}$) depends on the choice of convection model in the atmosphere $\alpha_{\rm atm}$, and in the interior $\alpha_{\rm in}$, and on the matching point $\tau_{\rm match}$. Use of FST both in the atmosphere (the NEMO non-grey atmospheric grid by Heiter et al., 2002) and in the interior provided instead a smooth match, independent from $\tau_{\rm match}$. The temperature gradient inside solar models, and its dependence on the three parameters so on three parameters, $\alpha_{\rm atm}$, $\alpha_{\rm in}$ and $\tau_{\rm match}$, is shown in Figure 2. All models shown in Figure 2 fit the solar T$_{\rm eff}$, but they differ up to ~200 K in the Hayashi track location (Montalbán et al., 2004). The recent models by Baraffe et al. (2015) make a more uniform choice for $\alpha_{\rm atm}$ and $\alpha_{\rm in}$, and the resulting T$_{\rm eff}$'s are closer to those of other set of tracks.

Partial attempt to improve knowledge of convection efficiency is to use 2–3D radiative hydrodynamic (e.g. Freytag et al., 1996; Stein & Nordlund, 2000; Asplund et al., 2000) (RHD) simulations of stellar surface convection. The idea is to approximate the gradient in the whole convective region with the value

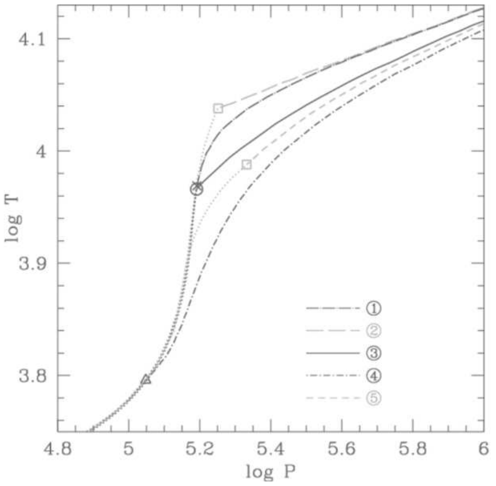

Fig. 3. From Montalbán et al. (2004), plot of log temperature (in K) versus log pressure (in cgs units) within the stellar atmosphere and interior, for solar models. Thick long-dashed line (1): FST model, in which the same convection model is adopted both in the atmosphere and interior. The MLT models stratification depends on the choice of the three parameters: the α value in the atmosphere and in the interior, $\alpha_{\rm atm}$ and $\alpha_{\rm in}$ and the matching optical depth $\tau_{\rm ph}$. For $\alpha_{\rm atm} = 0.5$ the lines are: grey long-dashed line (2): $\alpha_{\rm in}$=6.3, starting at $\tau_{\rm ph} = 100$ – square; solid line (3): $\alpha_{\rm in}$=2.3, starting at $\tau_{\rm ph} = 10$ – circle; short-dash-dotted line (4): $\alpha_{\rm in}$=1.75, starting at $\tau_{\rm ph} = 1$ – triangle. Finally the short-dashed line (5) corresponds to $\alpha_{\rm atm} = 1$ (from Hauschildt et al., 1999), $\alpha_{\rm in}$=1.75, starting from $\tau_{\rm ph} = 100$ – square. (Credit: Montalbán et al. (2004), reproduced with permission copyright ESO)

of mixing length which provides the same average gradient found by simulations. This does not say anything about the “true” gradient along the structure, but allows computation of “calibrated MLT” models. In spite of this, problems remain in the fit of some binary data and in the fact that these models predict too strong pre-MS solar lithium depletion (Montalbán & D’Antona, 2006), as we discuss in next section.

6. The light elements burning in pre-MS

6.1. Deuterium

The role of Deuterium in the proto-stellar evolution (Stahler, 1988; Palla & Stahler, 1991) has been put into evidence also in the disk–accretion models by Kunitomo et al. (2017), showing that the pre-MS initial stage of the solar mass depends on the abundance of deuterium in the accreting gas, even in the absence of accretion energy acquired by the core. It is probable that we see pre-MS low mass stars still in the phase of D-burning, and the transition from masses able to ignite deuterium to those which can not, due to degeneracy ($M \sim 0.013 M_\odot$ Spiegel et al., 2011) bears observable signatures in the color magnitude diagram.

6.2. Lithium

Lithium burning is the other important benchmark of pre-MS evolution. While recent attention of some models including disk accretion has been focused on the possible burning of Lithium very early during the protostellar phase, most observations show a (qualitative) agreement with the expectation of standard burning along the Hayashi track evolution.

D’Antona & Mazzitelli (1994) (Figure 15) predicted that stellar ensembles of different young ages should show a “lithium chasm” (although it was not yet named in this way!), a region in luminosity (and $T_{\rm eff}$) where Lithium is absent from the spectra. In fact, going down with $T_{\rm eff}$ (or luminosity), Lithium disappears from the spectra (at masses $\sim$0.7–0.9$M_\odot$, depending on the models), but it reappears at smaller luminosities ($T_{\rm eff}$’s) *depending on the sample age*. This is a further evidence of the role of the thermal timescale, dictating a slower increase of the central temperature of a contracting object, up to the $\sim 2.5 \times 10^6$ K needed to burn lithium by proton capture. So the larger masses – for which the envelope is still convective at the lithium burning temperature – deplete lithium early (already at 5 Myr), but the smaller masses take a longer time to do that. The right boundary of the "chasm", the Lithium Depletion Boundary or LDB, can be used as an independent way to date clusters. There have been recent attempts to determine the uncertainty in the LDB (Jeffries et al., 2013; Tognelli et al., 2015), the conclusion by Jeffries et al. (2013) is that the LDB allows a better determination of age than the turnoff, hampered by uncertainties in the treatment of the convective H-burning core extra-mixing (or whatever physical mechanism this overshooting hides).

The 'left' (higher mass) boundary of the Lithium chasm is the standard pre-MS lithium depletion. The solar Li abundance must results from both pre-MS plus "long term" depletion mechanisms, as it can be inferred from observations in clusters of increasing ages. This problem has been debated for nearly 50 years! Montalbán & D'Antona (2006) showed that "calibrated MLT" models (see Section 5) destroy too much Li in pre-MS. Recent models are compatible with pre-MS Li depletion in open clusters only for not very efficient convection (small α_{MLT}). As an example, in spite of reduced abundances in the solar atmosphere (Asplund et al., 2009), Tognelli et al. (2012) *can not* fit the young open clusters Lithium data using the same value of α needed to fit the main sequence.

7. Non-standard pre-MS models

Torres et al. (2006) comparing the masses and radii derived from binary data, shows that often the observed radii are larger than the models. This can be due to stellar activity (rotation) in eclipsing binaries. Also single pre-MS stars are generally active. Ventura et al. (1998) and D'Antona et al. (2000) show that the presence of a magnetic field may inhibit convection in pre-MS. These models have larger radii and are consistent with the scarce lithium depletion at $\sim 1 M_\odot$. Chabrier et al. (2007) reach similar conclusions for low mass stars and brown dwarfs in eclipsing binaries. Other models including the effect of a magnetic field on the structure are available (Feiden & Chaboyer, 2012; Feiden, 2016). Note that, if inhibition of convection is an important in pre-MS, not even at low masses we have reliable models!

A different approach is taken by Somers & Pinsonneault (2014), who show that rotating stars have inflated radii and lower Li-depletion, explaining the correlation Li-rotation and the spread in Li abundances among the Pleiades stars. Note that rotation with no radius inflation increases Li-depletion (Somers & Pinsonneault, 2015).

8. Conclusions

The hydrostatic contraction models are still of some value for age - mass determinations at 'reasonable' ages (above $\sim 10^6$yr), but disk accretion must be better modeled. Deuterium burning may still be the key to understand the observed location of T Tauri stars. Still the uncertainties in the mass–age determinations from models are large, due to convection modeling and non-standard physics needed to understand Lithium depletion. Burning of light elements remains a powerful signature of hydrostatic evolution.

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References

Allard, F., et al. 2001, ApJ, 556, 357
Asplund, M., Ludwig, H.-G., Nordlund, Å., & Stein, R. F. 2000, A&A, 359, 669
Asplund, M., et al. 2009, ARA&A, 47, 481
Baraffe, I., et al. 1998, A&A, 337, 403
Baraffe, I., Chabrier, G., & Gallardo, J. 2009, ApJ, 702, L27
Baraffe, I. & Chabrier, G. 2010, A&A, 521, A44
Baraffe, I., et al. 2015, A&A, 577, A42
Canuto, V. M. & Mazzitelli, I. 1991, ApJ, 370, 295
Canuto, V. M., Goldman, I., & Mazzitelli, I. 1996, ApJ, 473, 550

Chabrier, G., Gallardo, J., & Baraffe, I. 2007, A&A, 472, L17

Da Rio, N., et al. 2012, ApJ, 748, 14

D'Antona, F. & Mazzitelli, I. 1994, ApJS, 90, 467

D'Antona, F. & Mazzitelli, I. 1997, MmSAI, 68, 807

D'Antona, F., Ventura, P., & Mazzitelli, I. 2000, ApJ, 543, L77

Dotter, A., Chaboyer, B., Jevremović, D., et al. 2007, AJ, 134, 376

Feiden, G. A. 2016, A&A, 593, A99

Feiden, G. A. & Chaboyer, B. 2012, ApJ, 761, 30

Freytag, B., Ludwig, H.-G., & Steffen, M. 1996, A&A, 313, 497

Giulia Ubeira Gabellini, M., et al., & HST Treasury Program on the Orion Nebula Team. 2016, American Astronomical Society Meeting Abstracts, 227, 431.06

Hartmann, L., Cassen, P., & Kenyon, S. J. 1997, ApJ, 475, 770

Hartmann, L., Herczeg, G., & Calvet, N. 2016, ARA&A, 54, 135

Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ, 512, 377

Hayashi, C. 1966, ARA&A, 4, 171

Heiter, U., Kupka, F., van't Veer-Menneret, C., et al. 2002, A&A, 392, 619

Herbig, G. H. 1977, ApJ, 217, 693

Herbig, G. H. 1989, European Southern Observatory Conference and Workshop Proceedings, 33, 233

Iben, Jr., I. 1965, ApJ, 141, 993

Jeffries, R. D., et al. 2013, MNRAS, 434, 2438

Kunitomo, M., et al. 2017, A&A, 599, A49

Larson, R. B. 1969, MNRAS, 145, 271

Mercer-Smith, J. A., Cameron, A. G. W., & Epstein, R. I. 1984, ApJ, 279, 363

Montalbán, J. & D'Antona, F. 2006, MNRAS, 370, 1823

Montalbán, J., et al. 2004, A&A, 416, 1081

Palla, F. & Stahler, S. W. 1991, ApJ, 375, 288

Palla, F. & Stahler, S. W. 1992, ApJ, 392, 667

Palla, F. & Stahler, S. W. 1993, ApJ, 418, 414

Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593

Somers, G. & Pinsonneault, M. H. 2014, ApJ, 790, 72

Somers, G. & Pinsonneault, M. H. 2015, ApJ, 807, 174

Spiegel, D. S., Burrows, A., & Milsom, J. A. 2011, ApJ, 727, 57

Stahler, S. W. 1983, ApJ, 274, 822

Stahler, S. W. 1988, ApJ, 332, 804

Stahler, S. W., Palla, F., & Salpeter, E. E. 1986, ApJ, 302, 590

Stahler, S. W., Shu, F. H., & Taam, R. E. 1980a, ApJ, 241, 637

Stahler, S. W., Shu, F. H., & Taam, R. E. 1980b, ApJ, 242, 226

Stein, R. F. & Nordlund, Å. 2000, Sol. Phys., 192, 91

Tognelli, E., Prada Moroni, P. G., & Degl'Innocenti, S. 2011, A&A, 533, A109

Tognelli, E., Degl'Innocenti, S., & Prada Moroni, P. G. 2012, A&A, 548, A41

Tognelli, E., Prada Moroni, P. G., & Degl'Innocenti, S. 2015, MNRAS, 449, 3741

Torres, G., et al. 2006, ApJ, 640, 1018

Ventura, P., et al. 1998, A&A, 331, 1011

Vorobyov, E. I. & Basu, S. 2005, ApJ, 633, L137

Vorobyov, E., Elbakyan, V., Hosokawa, T., et al. 2017, ArXiv e-prints