A primer in Central Stars of Planetary Nebulae and related objects

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As their name indicates these stars are located in the center of bright gaseous nebulae known as planetary nebulae. The first Planetary Nebula (PN, plural Planetary Nebulae; PNe) was discovered by Messier in 1764 and known today as the Dumbbell nebula or M27 (Messier 1774). The misnomer planetary nebula was given probably by Herschel in 1785 (Kwok 2000) due to their similar appearance to the greenish disk of a planet. Hubble (1922) found a correlation between the magnitude of the PN with that of their central stars and argued that the emission-line spectrum was the result of the absorption and reemission of radiation from the star. This idea was further developed by Menzel (1922), who suggested that all emission beyond the Lyman limit was used to ionize the hydrogen (H) atom, and by Zanstra (1927) who qualitatively determined the mechanism by which H and helium (He) lines are emitted as a result of the recombination of nucleus and free electrons in the nebulae (see Kwok 2000). A description of the recent advances in the study of PNe can be found in Zijlstra (2015).

Nowadays we understand that Central Stars of Planetary Nebulae (CSPNe) trace a fast transition stage between the Asymptotic Giant Branch (AGB) Stars and White Dwarfs (WDs). Stars with masses initially between ~ 0.8 and ~8 times the mass of the sun evolve to the AGB after the exhaustion of He in their cores (Herwig 2005). At this point the stars consist of a degenerate carbon(C)-oxygen(O) core surrounded by a He-burning shell, a H-burning shell, and on top of the latter a massive H-rich envelope which consist mostly of material not processed by nuclear reaction (see Fig. 1). In between the H- and He- burning shells lies a region typically referred to as the intershell, which is rich in He, C and, sometimes, also O (see Herwig 2005). During the AGB two things that are key for the understanding of central stars of PNe take place: first, due to the cold temperatures reached in the extended atmospheres of AGB stars dust forms which leads to the development of very strong stellar winds up to 10^{-4} M_{sun}/yr (Höfner & Olofsson 2018); second, the He-burning shell becomes regularly unstable giving rise to almost periodical He-shell flashes also known as thermal pulses (Kippenhahn et al. 2012). The former is the key process determining the duration of the AGB phase as the winds efficiently erode the H-rich envelope which is the ultimate fuel reservoir for the H-burning shell, while the latter leads to the development of several convective regions whose interplay finally leads to the enrichment of the outer envelope with nucleosynthesised material that can be observed, i.e. mostly He, C or N, but also O and slow neutron capture elements, see Karakas & Lattanzio (2014).

In the simplest picture, Planetary Nebulae (PNe) are formed by low- and intermediate-mass stars after the strong stellar winds erode the H-envelope leaving only a light cover of ≤0.01 solar masses (Paczynski 1971, Schoenberner 1979, Vassiliadis & Wood 1994, Bloecker 1995, Miller Bertolami 2016). At that point, stars contract and heat up, crossing the HR-diagram at constant luminosity, first as compact and probably dust-embedded objects known as proto-PNe and then becoming sufficiently hot and bright to ionize the previously ejected material (Shklovsky 1957, Abell & Goldreich 1966, Paczynski 1970). Fig. 2 shows the typical evolution of stars from the main sequence to the CSPNe and white dwarf phases. The formation and detectability of PNe depends strongly on the interplay between two different timescales: the evolutionary timescale of the central star of the PN (CSPN), which provides the ionizing photons, and the dynamical timescale of the circumstellar material (Jacob et al. 2013). As a consequence low-mass stars might never form a PNe, and consequently those stars cannot be considered CSPNe. Those stars are known in old stellar populations as UV-bright stars (Brown et al. 2008, Moehler et al. 2019). A similar distinction is done earlier immediately after the departure from the AGB, when the star is not hot enough to ionize the surrounding medium, these objects are usually named “post-AGB” stars and a subgroup of them (those that will evolve to form a PN) are named proto-PNe (Lagadec 2018).

Early post-AGB evolution is expected to be relatively slow, with proto-PNe/post-AGB objects expected to evolve at a rate of $dT_{eff}/dt \sim 0.3$–3 K/yr at $T_{eff}\sim$5000K, with the actual value depending on the mass of the star (Miller Bertolami 2016, 2019). Evolution becomes much faster at later times, increasing to values of $dT_{eff}/dt \sim 3$–1000 K/yr at $T_{eff}\sim$10000K for stars with masses in the range of 0.53 to 0.7 M_{sun}. This fast evolution is kept during the early evolution as central stars of planetary nebulae (i.e. once $T_{eff}>$20000K). As already shown by Paczynski (1971), the evolutionary timescale of CSPNe is highly dependent on the mass of the star. State-of-the-art simulations of the post-AGB/CSPNe phase show that the time required for H-burning objects to evolve from $T_{eff}\sim$7000K to its maximum effective temperature, at $T_{eff}>$100000K, goes from about ~30000yr for stars in the lower mass range (~0.53M_{sun}) to less that 100yr for those stars with masses larger than 0.8M_{sun} (Miller Bertolami 2016, 2019).

The simple picture mentioned above is challenged by the detection of about 20% of close binary stars in PNe, and by the fact that the Hubble Space Telescope revealed that about 80% of PNe show different degrees of asphericity (Jones & Boffin 2017, Jones 2018, Boffin & Jones 2019). Additionally, the milliarcsec study of proto-PNe and AGB stars seems to suggest that most of the AGB stars observed will not form bipolar planetary nebulae, while most of the proto-PNe are likely to form bipolar PNe (Lagadec 2018). While small departures from spherical symmetry in PNe can be due to the action of magnetic fields, stellar rotation, the presence of planetary systems and substellar companions or even a wide stellar partner, there is consensus that highly aspherical PNe are linked to the formation of close binary systems. These close binary CSPNe, and PNe, are expected to be formed after a common envelope phase, in which two stars orbit inside a single, shared envelope (Ivanova et al. 2013). This phase is expected to end either in the spiral-in and merging of the two stars, or in the formation of a close binary system, together with the highly axisymmetric ejection of the common envelope material. Given that PNe last for only <30000 yr such close binary systems surrounded by PNe would represent a very recent stage of post-common envelope systems and, consequently a key for understanding the common envelope phase itself. While the number of known binary central stars is of about 20% some authors suggest that the total number of binary central stars can be as high of 80% (Jones & Boffin 2017). Interestingly even though most close-binary systems comprise an evolved star and a low-mass main sequence companion, there is a significant number of systems formed by two evolved compact stars; these systems are known as double-degenerate systems, and unless they are eclipsing they are very difficult to detect (Jones & Boffin 2017). These systems are particularly interesting as due to their very close orbits such systems are expected to merge due to gravitational wave radiation, leading to either the formation of H-deficient stars such as R Cor Bor (RCrB) Stars (Saio & Jeffery 2002) or to the occurrence of a Type Ia supernova (SN Ia) through the double-degenerate scenario (Webbink 1984; Iben & Tutukov 1984). One of such systems, Henize 2-428, has attracted a great deal of interest as it might be the first identification of a SN Ia progenitor within the double degenerate scenario (Santander-Garcia 2015). However, a recent redetermination of the masses in Henize 2-428 system with a careful consideration of the contamination of the spectra by diffuse interstellar bands indicates that the total mass does not exceed the Chandrasekhar mass limit and will probably not produce a SN Ia (Reindl et al. 2020).

Even in the case of single stars (or wide binary systems) the evolution of the central star can be more complex than the simple scenario outlined before. In fact the detection of some single CSPNe returning to the AGB in timescales of years or, decades, such as FG Sge, V4334 Sgr, V605 Aql, and SAO 244567 (Duerbeck et al. 2000, van Genderen & Gautschy 1995, Clayton & De Marco 1997, Reindl et al. 2017) indicate not only that some CSPNe are single stars but also that they can undergo a late thermal pulse event (Schoenberner 1979). In the late thermal pulse scenario, the last thermal pulse takes place when the central star is contracting away from the AGB into the white dwarf cooling track (Bloecker 2001). As a consequence of the sudden energy injection by the He-shell flash the star expands back to the AGB creating a "Born Again AGB star" (Iben 1984) where it stays for some time before contracting again to the white dwarf phase, this time likely as a H-deficient object. In addition of being a stark proof of the connection between AGB stars and PNe, V4334 Sgr might also offer clues of how bipolar PNe can be shaped also around single stars (van Hoof et al. 2018). Depending of the timing of the late He-shell flash the star may become H-deficient as a consequence of the burning of the remaining H-rich envelope in the so called "very late thermal pulse" (VLTP) scenario, or in the case of the so called "late thermal pulse" (LTP) scenario as a consequence of the dilution of the relatively massless H-envelope into the intershell region of the star (see Werner & Herwig 2006). In both cases the star will first become a H-deficient giant and, then, will heat-up and contract for a second time, now as a H-deficient object with a He-, C- and O-rich surface composition to form a H-deficient CSPNe (see Fig. 2). Classic examples of these CSPNe are the central stars of Abell 30 and Abell 78 (Iben et al. 1983). Recently Guerrero et al. (2018) identified the central star of HuBi 1 as a newly born H-deficient CSPNe.

In fact the late thermal pulse scenario is key for our understanding of the formation of a about 20% of CSPNe which show a H-deficient composition (Weidmann & Gamen 2011, Weidmann et al. 2018), and the recent catalogue by Weidmann et al. (2020) suggests that the ratio of H-deficient CSPNe might be even larger. Spectroscopically, CSPNe show a wide diversity of spectral types, both as a consequence of large differences in surface temperature and chemical composition. A description of the key optical lines for the spectral classification of CSPNe is given by Weidmann et al. (2020). Globally CSPNe can be separated into two main groups, CSPNe with "normal" H/He surface compositions with spectral types O(H), Of(H), hgO(H), OfWR(H) (see Mendez 1991) and H-deficient CSPNe of spectral types [WC], [WO], [WN], PG1159, [WC]-PG1159, O(He), O(C), and DO (Acker & Neiner 2003, Werner & Herwig 2006, Crowther 2008, Todt & Hamann 2015). In particular the group of H-deficient stars seems to be formed by two separate groups, a main C-dominated H-deficient evolutionary sequence formed by [WCL] → [WCE] → [WC]-PG1159 → PG1159 → DO WD (and then into DA or DB WD, depending on the total ammount of H-left in the star) which is linked to the late thermal pulse scenario in single stars (or wide binaries) and a second He-dominated evolutionary sequence formed by RCB → EHe → sdO(He) → O(He) → DO WD, which is probably linked to WD mergers in close binaries, and thus, linked to the post-common envelope evolution.

Some H-deficient CSPNe with PG1159 and [WC] spectral types belong to a small subgroup of variable stars known as GW Vir (Grauer & Bond 1984). These objects exhibit multiperiodic lightcurves that are understood to be caused by high-radial-order, low-degree g-mode (non-radial) pulsations. Typical observed pulsation periods are in the range from 300s to 3000s, and are explained by the action of the classic $\kappa-\gamma$ mechanism due to partial ionization of C and O, both of which are extremely abundant in the envelope of these stars (see Althaus et al. 2010, Córsico et al. 2019, and references therein). The existence of multiperiodic lightcurve variations opened the possibility of performing asteroseismological mass determinations for these objects (see Althaus et al. 2010), which are in general, in agreement with those coming from the comparisons of NLTE spectroscopical determinations with stellar evolution tracks (Werner & Herwig 2006, Miller Bertolami & Althaus 2006).

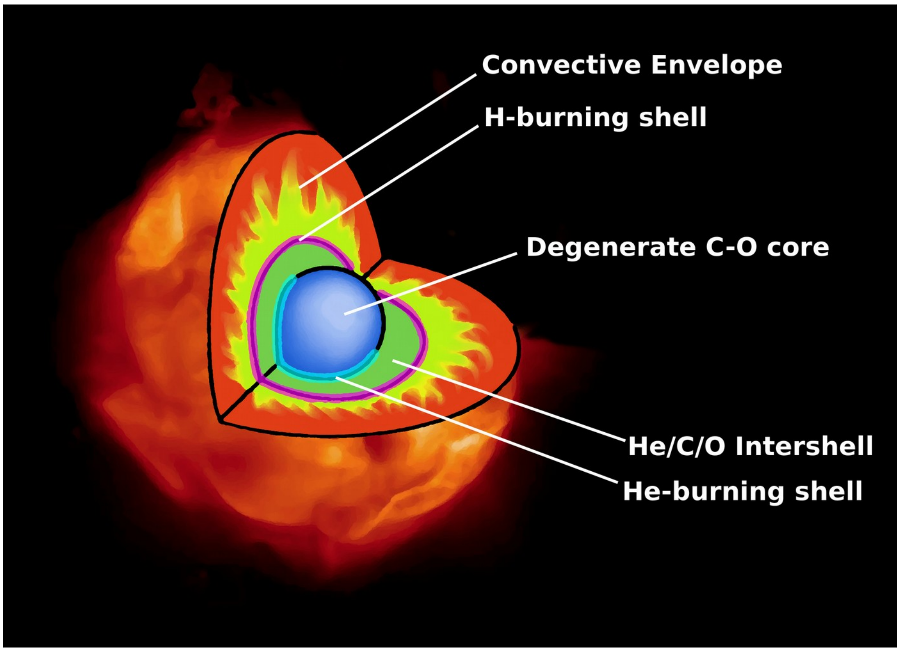

Figure 1: Schematic diagram of the internal structure of an AGB star

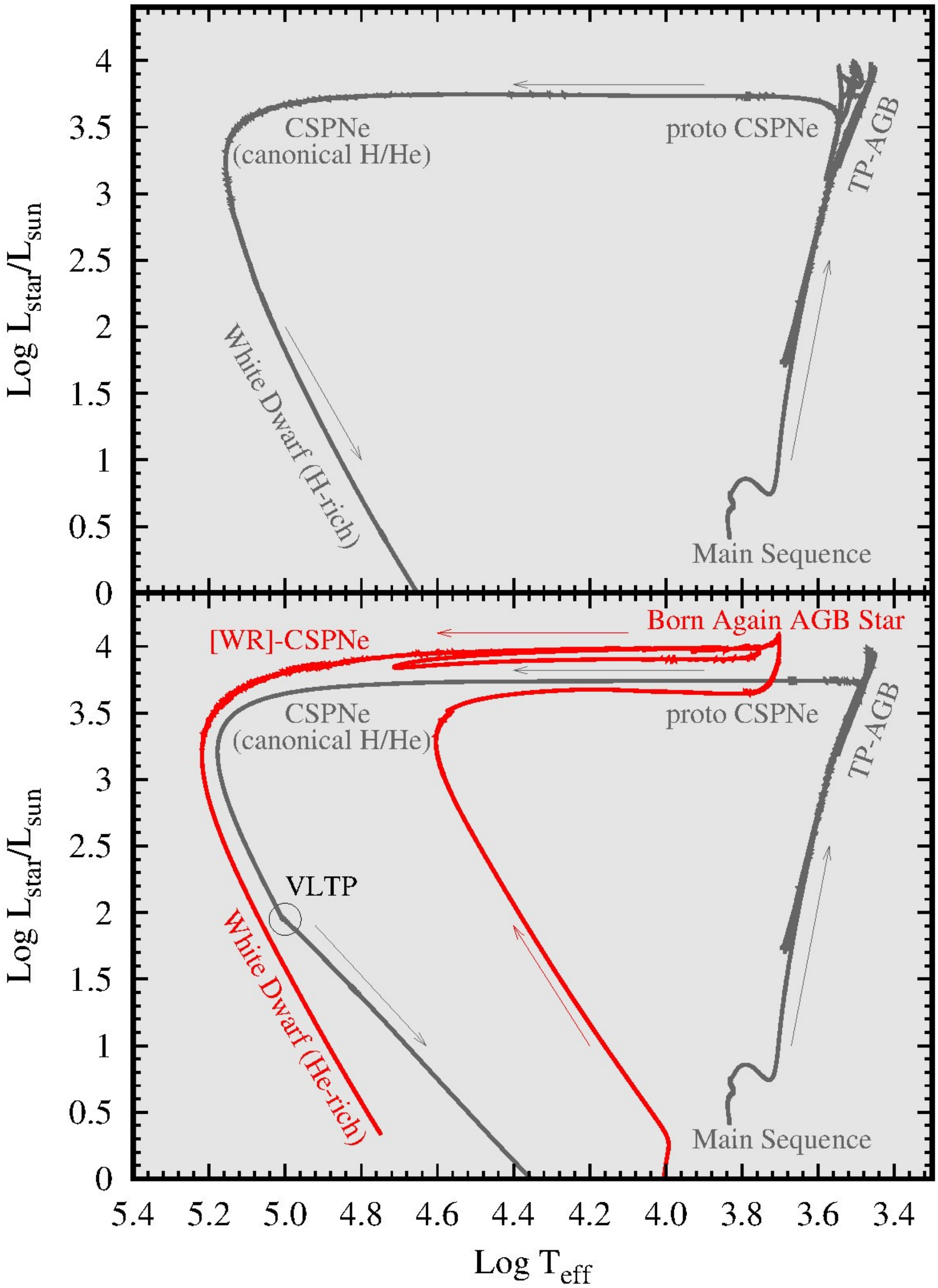

Figure 2: Evolution of an initially 1.25 solar mass star to the CSPN phase. Upper panel, canonical post-AGB evolution. Lower panel, formation of a H-deficient CSPN after a VLTP event.

Biblography:

-Abell, G. O., & Goldreich, P. 1966,PASP, 78, 232
-Acker, A., & Neiner, C. 2003, A&A, 403, 659
-Althaus, L.G., Córsico, A.H., Isern, J., and García-Berro, E.: 2010, Astron. Astrophys. Rev., 18, 471
-Blöcker, T. 1995, A&A, 297, 727
-Blöcker, T. 2001, Ap&SS, 275, 1
-Boffin, H. M. J. & Jones, D. 2019, The Importance of Binaries in the Formation and Evolution of Planetary Nebulae, Springer Nature
-Brown, T. M., Smith, Ed, Ferguson, Henry C., et al. 2008, ApJ, Vol. 682, Issue 1, pp. 319-335
-Córsico, A.H., Althaus, L.G., Miller Bertolami, M.M., and Kepler, S.O.: 2019, Astron. and Astrophysi. Rev., 27, 7
-Crowther, P. A. Hydrogen-Deficient Stars ASP Conference Series, Vol. 391. Edited by Klaus Werner and Thomas Rauch. San Francisco: Astronomical Society of the Pacific, 2008., p.83
-Darquier, A. 1777. Observations astronomiques, faites à Toulouse (Astronomical observations, made in Toulouse). Avignon: J. Aubert, (and Paris: Laporte, etc.)
-Duerbeck, H. W., Liller, W., Sterken, C., Benetti, S., et al. 2000, ApJ, Volume 119, Issue 5, pp. 2360-2375.
-Grauer, A.D., and Bond, H.E.: 1984, ApJ, 277, 211.
-Guerrero, M. A., Fang, X., Miller Bertolami, M. M., Ramos-Larios, G., et al. 2018, Nature Astronomy, Volume 2, p. 784-789
-Hrivnak, B. J., Lu, W., & Nault, K. A. 2015, AJ, 149, 184
-Herwig, F. 2005, ARA&A, 43:1, 435-479
-Höfner, S. & Olofsson, H. 2018, Astron. Astrophys. Rev. 26: 1.
-Hubble, E. 1922, ApJ, 56, 400-438
-Iben, I., Jr., Kaler, J. B., Truran, J. W., Renzini, A. 1983, ApJ, Vol. 264, p. 605-612
-Iben, I., Jr. 1984, ApJ, Vol. 277, p. 333-354
-Iben, I., Jr., & Tutukov, A. V. 1984,ApJS,54, 335
-Ivanova, N., Justham, S. , Chen X., De Marco, O., et al. 2013, Astron. Astrophys. Rev., 21:59
-Jones, D., & Boffin, H. M. J. 2017. Nature Astronomy, 1(5), 0117.
-Jones, D. 2018, The Impact of Binaries on Stellar Evolution, Beccari G. & Boffin H.M.J. (Eds.), Cambridge University Press., arXiv:1806.08244
-Jacob, R., Schönberner, D., Steffen, M. 2013, A&A, Volume 558, id.A78, 21 pp.
-Karakas, A. I., & Lattanzio, J. C. 2014, PASA, 31, 30
-Kippenhahn, R., Weigert, A., & Weiss, A. 2012, Stellar Structure and Evolution (New York: Springer)
-Kwok, S. 2000, The Origin and Evolution of Planetary Nebulae, Cambridge University Press.
-Lagadec, E., 2018, Galaxies, 6, 99, doi:10.3390/galaxies6030099
-Mendez, R. 1991, Evolution of Stars: The Photospheric Abundance Connection, 375, International Astronomical Union. Symposium no. 145, Kluwer Academic Publishers, Dordrecht, 1991., p.375
-Messier C. 1774, "Catalogue des Nébuleuses et des Amas d'Étoiles," Memoires Academie Royale des Sciences pour 1771 (Paris, 1774), pp. 435 ff.
-Menzel, D. 1926, Publications of the Astronomical Society of the Pacific, Vol. 38, No. 225, p.295
-Miller Bertolami, M.M., and Althaus, L.G.: 2006, A&A, 454, 845.
-Miller Bertolami, M.M.: 2016, A&A, 588, A25.
-Miller Bertolami, M.M.: 2019, Why galaxies care about AGB stars IV. IAUS 343. Eds. F. Kerschbaum, M. Gronewegen, H. Olofsson, & V. Baumgartner, arXiv:1910.01013
-Moehler, S., Landsman, W. B., Lanz, T., Miller Bertolami, M. M. 2019, A&A, Volume 627, id.A34, 15 pp.
-Paczyński, B. 1970, Acta Astron., 20, 47
-Paczynski, B. 1971, Acta Astron., 21, 417
-Reindl, N., Rauch, T., Werner, K., Kruk, J. W., Todt, H. 2014, A&A, Volume 566, id.A116, 23 pp.
-Reindl, N., Schaffenroth, V., Miller Bertolami, M. M., Geier, et al. 2020, A&A, Forthcoming article, DOI: 10.1051/0004-6361/202038117
-Reindl, N., Rauch, T., Miller Bertolami, M. M., Todt, H., Werner, K. 2017, MNRAS: Letters, Volume 464, Issue 1, p.L51-L55
-Saio, H, Jeffery, C. S., MNRAS, Volume 333, Issue 1, pp. 121-132.
-Santander-Garcia, M., Rodriguez-Gil, P., Corradi, R.L.M., Jones, D., et al. Nature 2015, 519, 63–65.
-Schönberner, D. 1979, A&A, 79, 108
-Schoenberner, D., Jacob, R., Steffen, M., & Sandin, C. 2007, A&A, 473, 467
-Shklovsky, I. S. 1957, in: G. H. Herbig (ed.), Non-stable stars, proceedings from IAU Symposium no. 3,Cambridge University Press,, p. 83
-Todt, H., Hamann, W. -R. Wolf-Rayet Stars: Proceedings of an International Workshop held in Potsdam, Germany, 1-5 June 2015. Edited by Wolf-Rainer Hamann, Andreas Sander, Helge Todt. Universitätsverlag Potsdam, 2015., p.253-258
-Vassiliadis, E., & Wood, P. R. 1994, ApJS, 92, 125
-van Genderen, A. M., Gautschy, A. 1995, A&A, Vol. 294, p. 453-468
-Clayton, G. C., De Marco, O. 1997, AJ, v.114, p.2679
-van Hoof P., Kimeswenger S., Van de Steene G., Avison A., et al. 2018 Galaxies 2018, 6, 79, doi:10.3390/galaxies6030079
-Weidmann, W. & Gamen R. 2011, A&A 531, A172
-Weidmann, W., Gamen, R., Mast, D., et al. 2018, A&A, 614, A135
-Weidmann, W., Mari, M.B., Schmidt, E., etal. 2020, A&A, Forthcoming article, DOI: 10.1051/0004-6361/202037998
-Webbink, R. F. 1984,ApJ,277, 355
-Werner, K., Herwig, F. 2006, PASP, Volume 118, Issue 840, pp. 183-204.
-Zanstra, H. 1927, ApJ, vol. 65, p.50
-Ziljstra, A., 2015 Rev. Mex. de Astronomia y Astrofisica,51, 221–230