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Memorie della

Infant stars behave like teenagers

Le difficoltà delle stelle giovani

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Abstract. Many of the research topics I have wandered into over the years directly intersected with Francesco Palla's interests, though my appreciation of the importance of these topics usually came many years after his. Here, I touch upon our crossing paths regarding: the spectral energy distributions of Herbig Ae/Be stars, the clusters of low mass stars surrounding the Herbig stars, the location of young pre-main sequence stars in the theoretical HR diagram, the evidence for luminosity/gravity/age spreads of young stars, the initial mass function and the age dispersion in the Orion Nebula Cluster, stellar pulsations in young low mass stars, and finally, young star variability. Francesco made insightful contributions in all of these areas.

Key words. Stars: pre-main sequence – Stars: variables: T Tauri, Herbig Ae/Be – Stars: oscillations

1. Introduction

It is an honor to be here and to be asked to review the contributions of Francesco Palla in the area of young stars and young stellar clusters. While this *is* a review talk that covers many of the issues in the interpretation of young stars that remain vexing to us today, I am going to take a somewhat personal tour through the subject. I do this not to highlight my own work over the decades, but rather to elucidate how my meanderings in the study of young stars so frequently intersected with Franceso's work. I suspect my story is not unique, as he probably influenced many of us in similarly subtle ways.

As we all know, relative to our mature and relatively inactive Sun, the young accreting stars have strong "excess" emission at most wavelengths: from x-ray through optical, and from near-infrared through millimeter. Even the non-accreting sources show enhanced "activity". What draws many of us to the study of young stars is their combination of well-understood mainstream conduct, with more erratic and unpredictable behavior – like teenagers. More on this analogy later.

I was a brash graduate student – a mere academic teenager – when I first started interacting with Francesco. We had a brief email exchange in 1992 after I had seen the Palla & Stahler (1991) birthline paper. I brazenly wrote to him asking to be on his preprint list (this was the only way researchers knew about the papers of colleagues in the same field – before arxiv). Francesco of course responded very politely to my email; as a result I felt somehow justified and accepted in the field. The following year, in 1993, we had a more protracted chain of correspondence about the construction of HR diagrams and the different ways of estimating both stellar temperature and stellar luminosity, in particular debating whether one should/could account for the circumstellar contributions to the observables, and how. More on this topic later, as well.

2. Crossing scientific paths

2.1. Circumstellar material

The publication context for these conversations was my very first paper – on the spectral energy distributions of the Herbig Ae/Be stars (Hillenbrand et al., 1992) which was roughly contemporaneous with similar work by Berrilli et al. (1992), Natta et al. (1993), and Hartmann et al (1993) all attempting to explain the Herbig star spectral energy distributions. Each paper had a different interpretation of the relative role of underlying star-plus-disk/envelope vs accretion/infall in explaining the observations.

2.2. Young star clusters

I put circumstellar dust and gas modelling aside, and began to concern myself with the small clusters that surrounded the Herbig Ae/Be stars. I believe Francesco and I actually met first in 1993, at the Amsterdam meeting on "The Nature and Evolutionary Status of Herbig Ae/Be Stars", which I attended for my first topical conference in astronomy. Francesco and I discovered here, that both of us had been working on the BD+40 4124 region, which I studied as small cluster (Hillenbrand et al. 1995a), while he was interested in one of the outflows (Palla et al. 1995). Later, both my thesis (Hillenbrand, 1995b) and that of Francesco's student Leonardo (Testi et al. 1997) explored the correlation of cluster density in these small-number clusters with the mass of the most massive star: the defining Herbig Ae/Be star.

2.3. Pre-main sequence evolution

Beyond the simple density correlation that both of our groups had found for the Herbig Ae/Be clusters, I started working on the details of the surrounding clusters, and making HR diagrams for the small groups. In many cases there was a full IMF complement, extending through the late M spectral types. This work brought me to another intersection with Francesco as I struggled with deciphering the emerging modelling efforts in pre-main sequence evolution. Then, as now, the systematics among different groups due to different choices for opacities, convection prescription, initial radius, effects of accretion, etc. were important to consider before adopting any particular set of tracks.

At some point, the small number statistics in the Herbig Ae/Be clusters seemed limiting and not worth fighting, so I began to work on the Orion Nebula Cluster (ONC), which appeared more promising to understand. This interest spawned another extended round of correspondence with Francesco, in 1997 and 1998. Hillenbrand (1997) and Hillenbrand & Carpenter (2000) demonstrated that the IMF peaked above the hydrogen burning limit, around $\sim 0.2\ M_\odot$, and declined into the substellar regime (a result now consistent with the solar neighborhood field star distribution after 2MASS/WISE were able to sample beyond M into L and T spectral types).

Francesco, meanwhile, had gone beyond mere IMF study and was thinking also about age distributions. He highlighted in Palla & Stahler (1999) the rough consistency of the upper bound of the ONC luminosity vs temperature sequence with the birthline, and argued for the first time the accelerating star formation scenario. This paper also claimed that the IMF did not turn over, but we will forgive that.

Placing stars in the HR diagram when they are actively accreting is wrought with difficulty, as we have known for decades. Sorting out whether to simply integrate SEDs (assuming the luminosity has to emerge somewhere) vs finding a wavelength at which the accretion effects on the blue end vs the thermal emission effects on the red end, are minimized, so as to apply the wavelength-dependent bolometric correction, must be considered. How to determine and account for extinction is another major challenge. The continually evolving mass-luminosity relationship means that age and mass derivations, and all accompanying assumptions must be examined. And of course large samples are needed in order to determine the *form* as well as *shape* of the IMF.

2.4. Age spreads in clusters?

I became distracted for time working on the seemingly more well-behaved solar neighborhood active stars, and searching for debris disks and for evidence of planets around them. In part this was because I remained bothered by the lack of agreement in the HR diagram between the young cluster sequences and the gradually appearing pre-main sequence track sets – none of which seemed to eliminate the basic issue that for stars in the same cluster, the higher mass pre-main sequence stars appeared older than the lower mass, fully convective pre-main sequence stars. Hillenbrand et al. (2008) eventually presented for all clusters in the solar neighborhood that could be located in the HR diagram, the problem of the empirical cluster sequence mis-matches with theory, and the amplitude of the luminosity spreads. Although gaussian in log L, the luminosity spreads are larger than can be simply explained by known sources of uncertainty and systematic effects, and certainly imply the existence of age spreads when taken at face value. The age spreads were important to quantify both in their own right, for furthering our understanding of pre-main sequence stellar evolution (including stellar angular momentum evolution), and also for practical reasons such as making progress on important problems including the evolution of circumstellar disks, the related issue of time scales for planet building in different parts of the disk. According to the luminosity spreads, the age spreads decrease from a factor of ~5 below ~1 Myr, to <30% by ~10 Myr.

How can the reality of the luminosity spreads and their implications for age spreads be tested? One way is to review the systematics, that is, the intrinsic color and bolometric correction scales that must be assumed, and whether they are in fact appropriate for young pre-main sequence stars. I again mention the effects of extinction errors, which tend to be systematic due to methodology, but also have a random component. Exquisite photometry and high quality spectra for the placement of stars in the HR diagram should be an aim in reducing random errors as well. Another broad category is to review other effects that lead to scatter, such as: binarity, scattered light effects, accretion effects, and photometric variability. Confirmation of membership of any given star in a cluster should be ascertained; here the Gaia mission data products will make an enormous impact in securing cluster membership lists.

Let me mention a few details on the above. First, pursuing the route in the ONC of simply obtaining better data, under the guise of an HST Treasury program led by Massimo Robberto, Francesco and I formally were collaborators (Da Rio et al. 2009, 2010) though we actually had almost no interaction on the project. Da Rio et al. (2011) showed that, despite the much better data and analysis methods relative to Hillenbrand et al. (1997), the ONC HR diagram resulted in about the same stellar mass distribution (peaking above the hydrogen burning limit then turning over into the brown dwarf regime) and age distribution (~0.3 dex spread). I was, frankly, disappointed.

Now, what *has* appeared to work in reducing the luminosity spreads, is careful attention during decomposition of moderate dispersion optical spectra into: 1) the stellar photosphere, 2) veiling due to accretion, and 3) foreground extinction that reduces the summed star+accretion flux. Manara et al. (2013) and Frasca et al. (2017) have illustrated that in some cases, extreme motions in the HR diagram result from simultaneous fitting for these three components, compared to the standard technique of relying on spectral types and broadband colors. A reduction in luminosity spreads can also be achieved by considering the averages of time series photometry, so as to account for variability effects (Messina et al. 2017), and by cleaning historical membership lists using Gaia mission parallaxes and proper motions (Prusti et al., 2016), as illustrated by Hillenbrand et al. (2018).

A final way to test the apparent age spreads, is to find a different clock for the young clusters – one other than the traditional HR diagram isochrones. Correlations of surface gravity and of lithium abundance with stellar luminosity differences at fixed temperature is one approach, and there are also seismology checks in certain regimes of the HR diagram. Despite that White & Hillenbrand (2005) discussed one peculiar young object, St34, which showed obvious signatures of accretion yet lacked lithium, I was slower than Francesco in catching on to the value of the surface gravity and lithium measurements for investigating age spreads. But again, our paths intersected.

At the 2008 conference in Baltimore on "Young Star Ages", I was asked by Francesco to present his talk (because, as I later learned, his father had become ill). Included in Francesco's slides were his updated HR diagram work with Stahler, describing the accelerating star formation picture, and also discussion of several pre-main sequence age techniques that I had not really thought too deeply about before. Palla et al. (2005 and subsequent papers) were exploring the use of lithium depletion as a relative age diagnostic for young stars, first in the ONC and then in other clusters. Marconi & Palla (1998) had pointed out that some of the friends with which my story began – the Herbig Ae stars – actually crossed the canonical instability strip en route to the main sequence; by late in the subsequent decade, several such objects had in fact been observed to pulsate.

The exercise of giving someone else's talk was an interesting thing to do, and I think I grew from the experience. While we were each skeptical of some aspects of the other's methods and views on certain issues (for example, how to place stars in the HR diagram!), the important points here are that: 1) I think I managed to present both interpretations fairly, and 2) Francesco had entirely trusted me to do exactly that.

Inspired by that experience of taking a different perspective, my own conference proceedings for that meeting (Hillenbrand, 2009) included a correlation of the HR diagram based relative luminosity, with a spectral diagnostic of surface gravity among late type stars, as well as with the surface gravity inferred from the HR diagram-derived M and R values. Both diagrams hinted at a relation, but I remained skeptical about whether the quality of the data was sufficient for doing the job we demanded of it. To this day, there are not many reliable, true log g values derived from high quality spectral analyses for young pre-main sequence stars.

2.5. A new domain for pulsations?

That 2008 meeting was also the catalyst for discussions Francesco and I had in the early 2010's over coffee with Ann Marie Cody, then a student. Ann Marie was planning to base her entire PhD thesis on testing the Palla & Baraffe (2005) theory of pre-main sequence stellar pulsations at the low mass end, due to light element nuclear burning (ϵ mechanism) rather than the usual opacity (κ mechanism) that characterizes the classical instability strip. Francesco was nothing but encouraging, though he did advise that someone should probably improve the theory since there were rough predictions for the frequencies (1-4 hour periods) but little on the amplitudes. Cody & Hillenbrand (2014) reported no pulsations down to a few millimag levels on any time scale <7 hours. This is unfortunate, given that pulsation has been so successful in other areas of the HR diagram in determining quantitative stellar ages. If there are pulsations, they either can not grow to observable amplitudes, or they are unexpectedly damped by convection.

3. Connections to recent work

3.1. Fundamental stellar parameters

I want to talk a little now about some of the current work I have been doing with collaborators, and its connections to Francesco.

Among Francesco's 2008 conference slides that I presented, one was a comparison of several pre-main sequence stars with fundamental masses and radii (later published as Palla & Stahler 2001). With the recent ability of Kepler / K2 to survey several relatively nearby clusters, including the pre-main sequence low mass end of the Pleiades as well as the younger Upper Scorpius and Taurus regions, more double-line eclipsing binaries have been discovered and characterized. This

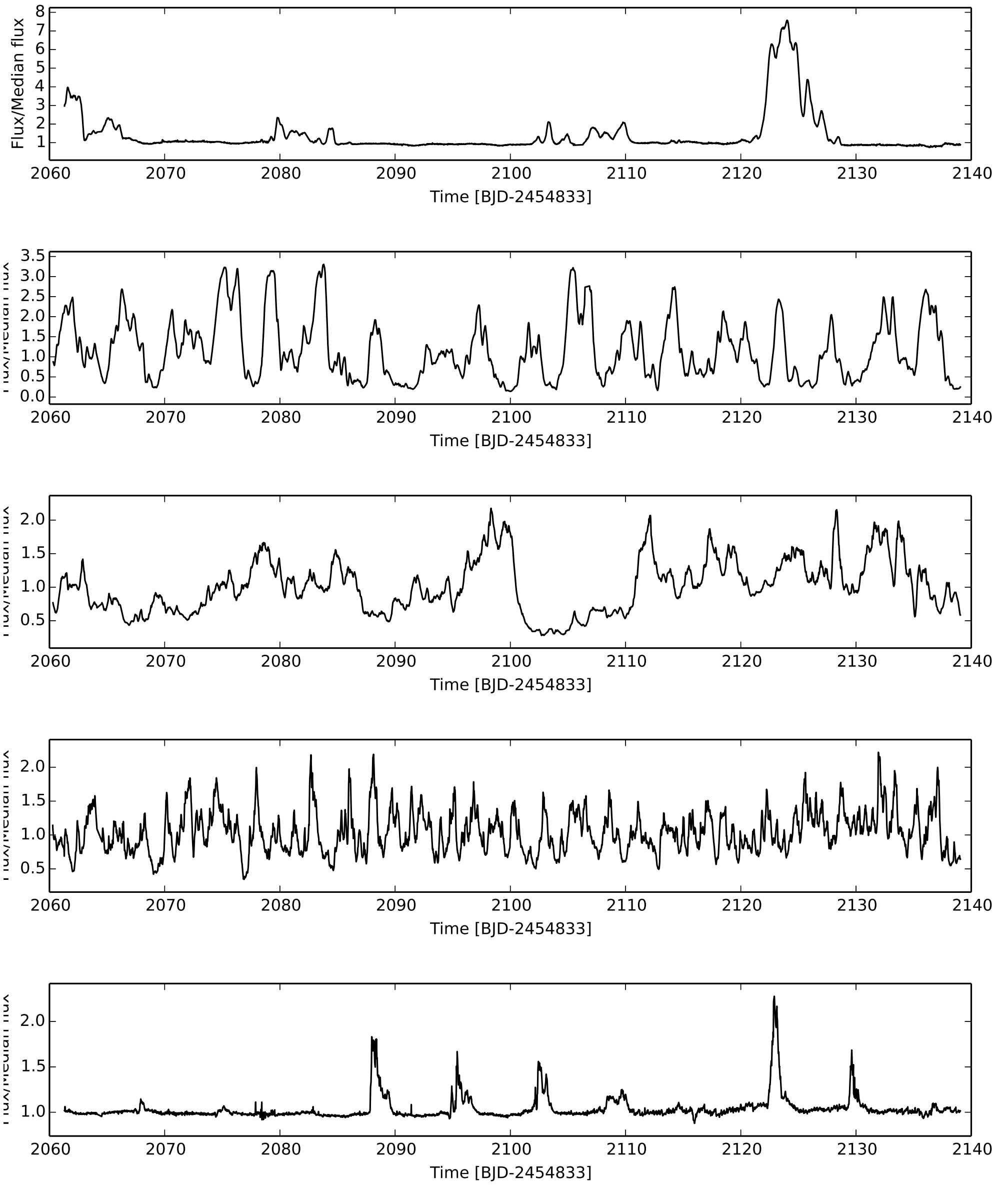

Fig. 1. Variability measured by Kepler/K2 of selected Upper Sco sources exhibiting "accretion burst" type light curves (reproduced from Cody et al., 2017). A range of amplitudes, timescales, quasi-periodicity, and discrete vs continuous burst behavior is seen.

work enabled David (2017) to derive empirical cluster isochrones in the fundamental plane of radius versus mass. While this has been done for spatially resolved multiple star systems whose components can be individually located in the HR diagram of L vs T (Hartigan, Strom,

& Strom, 1993; White et al. 1999; Kraus & Hillenbrand 2009), this is the first construction of R vs M cluster isochrones.

3.2. Variability in young stars

One area Francesco and I never discussed in our limited, but always meaningful interactions, was the photometric variability that is observed ubiquitously in young stars. This brings me back to my title, which I can now elaborate upon. Like young humans in the adolescent or "teenager" stage, young stars are:

- Active, variable, and often moody.
- Under the impression that everything in their sphere of influence orbits them.
- Still gaining mass.
- Able to oscillate between a steady low state, and more punctuated episodes of rapid accretion.
- Prone to instabilities, outbursts, and even outflows.
- Sometimes in long-term depressive states.
- Oftening surrounded by obscuring material.
- Hard to figure out!

What I would like to emphasize here, is the importance of, and especially the diversity of, variability patterns in young stars. Those who studied them in the past were doing "time domain astronomy" well before anyone called it that. The variability behaviors manifest photometrically, with amplitude ranges from percent level to several magnitudes, and time scales from sub-hour to multi-year, and often spectroscopically as well. There are two main families of variability behavior that are distinctively associated with young accreting stars: variable extinction, which preferentially causes dimming (e.g. Stauffer et al. 2015), and variable accretion, which preferentially causes brightening (e.g. Cody et al. 2017; see Figure 1). There is a continuum of behavior, of course, with another category the timescale-stochastic, but amplitude-symmetric patterns with near-equally down and up variations (e.g. Stauffer et al. 2016). Both the extinction-related dips and the accretion-related bursts can be periodic, likely due to the importance of the magnetosphere in the flow of gas and possible trapping of dust. Additionally, there is the large population of sinusoidal and semi-sinusoidal variations that are due to rotating star spots rather than being disk-related.

While fascinating study in its own right, young star variability also has quite practical implications for the main theme of this talk, which is pre-main sequence evolution. First, as well articulated by several other speakers at this conference, the extreme outburst events are interpreted as rapid accretion that is episodic and has substantial effects on the true paths of stars through the HR diagram. Second, is the impact of this variability on the main way we place stars in the HR diagram: by adopting a magnitude and an intrinsic spectral type (i.e. temperature, color and bolometric correction), and by calculating the extinction. Current "best practices" largely ignore the real implications of the variability on our methodologies.

What is clear, is that the variability offers us insights, even though it causes us significant difficulties.

4. Closing thoughts

I admired Francesco a lot, despite that I really did not know him very well, especially compared to many of you in the audience of this conference. Were he here with us, I would have looked forward to discussing with him the new results on eclipsing binaries, the complicated phase space of young star variability, recent theoretical work on pre-main sequence accretion histories, and of course the impacts of all of these on HR diagrams. I am forever grateful for Francesco's influence on me, even if from a great distance.

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