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EXors and the stellar birthline

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Abstract. EXors are young stars whose luminosities periodically increase by up to a factor of 100 within a year. Unlike the better-known FUors, their decay time is also relatively brief, and single objects have been observed to flare multiple times. A popular notion is that EXors represent an especially early phase of pre-main-sequence evolution. Mackenzie Moody and I have shown that classical EXors, those which are visible prior to outburst, have the same age range as classical T Tauri stars. However, embedded EXors, those seen in quiescence at infrared and submillimeter wavelengths, are indeed very young. They lie close to the birthline in the HR diagram. Photometrically, these objects are typical Class I or flat-spectrum sources. Thus, both categories include stars that are in the pre-main-sequence, and not the true protostellar, phase. An "embedded pre-main-sequence" phase should be included in a more complete description of low-mass stellar evolution.

Key words. Stars: pre-main sequence – Stars: variables: general

1. Introduction

One ubiquitous property of young stars is their variability. The stars which vary in the most dramatic fashion are the FUors. These objects, named for the prototype FU Ori, increase their luminosity by a factor of up to 100 in the course of a year or so, and then take many decades to fade (Vittone & Errico 2005). The recurrence time of any flareup is so long that we have never witnessed more than one such eruption in any star. As a consequence, our records of the actual flaring are generally rather sparse.

The observational situation is vastly improved for the less well-studied EXors. Like FUors, these low-mass, young stars brighten in a year by as much as a factor of 100. However, the decay lasts only a decade or less, comparable to the recurrence period of flares (Herbig 1989). Most of the several dozen known EXors have been seen to flare multiple times. Thus, the amount of data available to study the phenomenon is quite extensive. Nevertheless, the current attempts at modeling are even more inconclusive than for FUors, simply because few theorists have tackled the subject.

Even before attempting any direct assault on the physical cause of flaring, it is worthwhile asking how common the phenomenon actually is. EXors that are optically visible prior to an outburst are known to be classical T Tauri stars. Herbig (2008) observed that they are indistinguishable, both in spectroscopy and photometry, from other stars of this type (see his Fig. 10). EXor eruptions occur so frequently in any object that their total number would be vastly larger if most classical T Tauri stars had this behavior. Clearly this cannot be the case, i.e. only a small fraction of low-mass, pre-main sequence stars undergo this kind of outburst.

Classical T Tauri stars have disks, and these may be responsible, either directly or indirectly, for the flaring activity. Might this activity occur only in the very youngest subset of classical T Tauri stars? Such is the view of (Hartmann 2008). He and others have speculated that both FUor and EXor-type outbursts occur in all low-mass, young stars, the former when the object is still undergoing infall from its parent dense core. In this picture, the EXors are direct descendents of the FUors (see also Reipurth & Aspin 2010). The more frequent outbursts occur once the star is no longer embedded, but still very early in the optically visible pre-main-sequence phase (Hartmann 2008, Fig. 1.12).

The hypothesis of extreme youth is easy to test, at least in principle. One simply places all known, visible EXors in the HR diagram, and reads off stellar ages (and masses) from a set of underlying, pre-main-sequence tracks. One should, of course, put stars in the diagram according to their quiescent, pre-outburst effective temperatures and luminosities. Mackenzie Moody and I recently did this exercise (Moody & Stahler 2017).

We first tabulated essential data on all the known EXors, including a record of which stars are have binary companions. It turns out that most EXors are, in fact, binaries, either visual or spectroscopic. The binary periods are vastly discrepant from the recurrence time of outbursts –much longer for visual binaries, and much shorter for spectroscopic ones. This discrepancy suggests that binaries are not reponsible for triggering the flareups. However, finding additional companions with periods of about a decade would be very challenging in practice. Until such observations are undertaken, the question of whether companions trigger the outbursts must remain open.

Figure 1 is an HR diagram, which includes both a standard, zero-age main sequence and the pre-main-sequence evolutionary tracks of Palla & Stahler (1999). The open circles represent all of our tabulated EXors that are optically visible prior to outburst. Again, these are objects that are already known to be classical T Tauri stars. It is apparent that these "classical EXors" are *not* especially young, but have ages that span just the range one would expect. This finding is fully consistent with the earlier results of Herbig (2008).

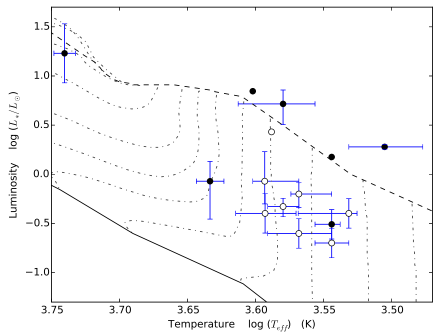

Fig. 1. Exors in the HR diagram. Open and filled circles represent classical and embedded EXors, respectively. The upper, dashed curve is the stellar birthline of ref, and the lower, heavy solid curve is the zero-age main sequence. The lighter, dashed curves are the pre-main-sequence tracks of ref. From right to left, the corresponding masses, in solar units, are: 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.5, 2.0, 2.5, 3.0, and 3.5.

However, there is an interesting twist to this story. Starting about a decade ago, a new type of EXor was identified (Lorenzetti et al. 2012). These are optically faint in quiescence, and their outbursts were picked up in large, infrared surveys. The spectral energy distribution of such an "embedded EXor" falls into the Class I, or occasionally, the flat-spectrum category (Fig. 2). Thus far, the strength and frequency of their outbursts appear similar to those of classical EXors, but manifested in the infrared. In some cases, the extinction diminishes substantially during outburst, but the flaring is intrinsic, and not simply a fluctuation in coverage by obscuring matter (see, e.g., Aspin & Reipurth 2009).

Placing embedded EXors in the HR diagram is more problematic than for their classical counterparts. For one thing, we rarely have a direct measure of the stellar luminosity, only the bolometric one. But these two quantities cannot differ greatly. If the bolometric luminosity were much higher, then the excess, accretion-powered component would also be

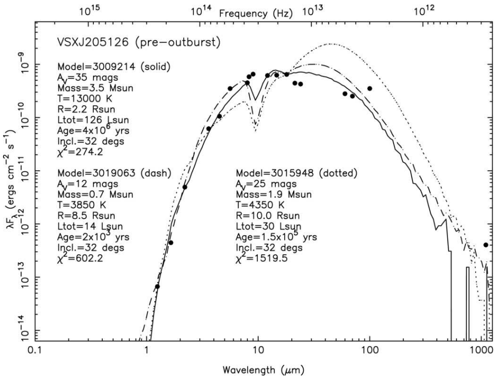

Fig. 2. Spectral energy distribution of V2492 Cyg, an embedded EXor. From Aspin (2011).

relatively large. Assuming this accretion stems from a disk, the lifetime of the latter would be unreasonably brief, much less than the star's own contraction (Kelvin-Helmholtz) time. In summary, it is probably safe to use the relatively accesible $L_{\rm bol}$ as a substitute for L_*, and we have done so in practice.

With the help of this device, we may now position all known embedded EXors in the HR diagram. In practice, we labeled EXors as embedded according to their observed flux at 12 μm, as compared to that in the visual band. Defining $R \equiv (\lambda F_\lambda)_{12} / (\lambda F_\lambda)_{\rm V}$, we take embedded EXors to be those with $R > 10$.

As seen by the filled circles in Figure 1, these objects mostly lie close to the stellar birthline. In other words, the embedded population *is* an especially young subgroup of pre-main-sequence stars. And we can be certain that they are indeed pre-main-sequence stars, as opposed to true protostars, because of the similarity of their flaring to classical EXors.[1]

These results suggest the following, amended picture for the early evolution of low-mass stars. During its initial, protostar phase, the object acquires the bulk of its mass through infall from its parent dense core. There follows a period during which the star, now contracting due to its self-gravity, is still enshrouded in a remnant envelope of gas and dust. It is only after the residual material disappears that the star emerges as an optically visible, pre-main-sequence object, a T Tauri star observationally. A small minority of pre-main-sequence stars undergo repeated flaring, both in their embedded and revealed stages. It is not at all clear physically how the remanant envelope is suspended during the "embedded pre-main-sequence" phase, nor how the envelope later vanishes. Nevertheless, the existence of embedded EXors demonstrates two general points. First, not all Class I sources are true protostars, and the terms should not be conflated. Second, the embedded pre-main-sequence phase needs to be included in a more complete account of low-mass stellar evolution. Future observational studies should probe more carefully the configuration of the remnant, dusty envelope, so that theorists can discern the balance of forces that allows it to persist.

[1] The few embedded EXors that lie well below the birthline are peculiar in other respects. For example, V1180 Cas may actually be undergoing periodic *decreases* of luminosity (Kun et al. 2011).

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