The Variability of Young Stellar Objects: An Update

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Abstract A brief update is provided on the nature of the variability of young stellar objects. The emphasis is on Type III variables, also known as UXORs or "dippers," which undergo periodic or aperiodic occultation by circumstellar material.

1. Introduction

Stars form when cold clouds of gas and dust in the galaxy become gravitationally unstable and collapse, over hundreds of thousands to millions of years, to a dense central object with a surrounding "circumstellar" (CS) or "circumbinary" (CB) disk. Initially, a star's main energy source is gravitational energy, released as it collapses and heats. Eventually the star is hot enough at its core to begin turning hydrogen into helium via nuclear fusion reactions. At this point the star settles into its stable "main sequence" phase and is generally constant in its light output at a level of 0.01 mag or less. Before it gets to that point it is known as a "pre-main sequence" (PMS) star. For a star like the sun this can last 30–50 million years so there are many such objects within reach of small telescopes. They have not had time to move far from their birth sites so they cluster in regions of high gas and dust density, such as the Orion nebula or the Taurus dark clouds.

PMS stars are universally variables, for a variety of reasons—see the review by Herbst (2012) for more detail. Since they are still clustered within their nebulous birth-gas clouds, they were originally called "nebular variables." As young stars, they spin 2 to 20 times faster than the Sun and have highly convective interiors. This combination of factors generates intense magnetic fields at their surfaces. They commonly have huge spots, analogous to sunspots but covering 10% or more of their photospheres. The growth and decay of these spots results in irregular variability on a timescale of months to years, while stellar rotation imprints a periodic variation of typically 2 to 10 days. This is referred to as Type I variability (Herbst *et al.* 1994) and can reach amplitudes of 0.5 mag or larger, although <0.1 mag is most common.

The very youngest PMS stars, those with ages under 1–10 million years or so, depending on mass, have not had time to fully dissipate their surrounding disk, either by accreting it, blowing it away with stellar winds, or condensing it into planets. In these objects, gas continues to spiral in towards the star, where it encounters an intense "magnetosphere" stretching up to 10 stellar radii from the surface. In this highly magnetized zone, gas is ionized and then levitated out of the disk to crash down onto the star's surface within polar rings, analogous to auroral rings on Earth. The energy released by this accretion drives sporadic variability of these stars on a timescale of hours to days. This is referred to as Type II variability and can reach amplitudes of 1 or 2 mag in some cases, although it is commonly much less than that (<0.1 mag). An extreme form of accretion variability is exhibited by a rare class of PMS stars known as FUORs, named after the prototype FU Ori (Herbig 1977). These objects show brightness increases of many magnitudes lasting for months or years followed by a slow decline to their original levels. This is attributed to a relatively brief period of substantially enhanced accretion, the cause of which remains uncertain.

A third type of PMS variability is also limited to those objects still young enough to be embedded in CS or CB disks, but in this case it is not accretion, but occultation, of the central star by matter within the disk, that causes the observed variations. Stars of this type are characterized by rather sudden fades in brightness that occur when some piece of CS material blocks all or part of their stellar photosphere from our vantage point here on Earth. In addition to being called Type III variables, these objects are also known as UXORs (after UX Ori) and "dippers," because of their brightness dips (Stauffer *et al.* 2015). Normally the variations are aperiodic and unpredictable, but some, such as AA Tau and V582 Mon (also known as KH 15D), are periodic. In the author's opinion, these are the most interesting objects to monitor and one place where AAVSO observers can continue to make important contributions to the study of PMS variables.

2. Observing Type III pre-main sequence stars

While it is generally agreed that the variations of Type III PMS stars are caused by occultation, since their spectral types do not change even as they fade by several magnitudes, the details of the process are far from understood. A basic issue is—what causes the opacity. Hydrogen and helium gas are normally transparent at optical wavelengths (unless hot and dense) so opacity is usually attributed to dust embedded within the gas. But dust cannot survive too close to a star. It should be vaporized within the magnetosphere, so if it is sheets of gas levitated by magnetic fields within the magnetosphere that are occulting the stellar surface the opacity may come from the hot, dense gas itself, not the dust. On the other hand, far from the star, only dust seems capable of blocking the starlight, but why is the dust so non-uniformly distributed? Some astronomers have suggested that the obscuring material is in the form of giant comets that occult the stars as they orbit them. Others have suggested warps in the accretion disk, which pass over the star like waves—sometimes periodically. Another possibility is that protoplanets in the disk could have large envelopes of dust around them and could periodically pass in front of the stars, causing the fades (Stauffer *et al.* 2018). In the case of CB disks, it can actually be the stars that are moving relative to the dust, that causes the brightness variations. V582 Mon is an excellent example of this (Aronow *et al.* 2018).

There are several features of Type III PMS objects that serve to make them particularly suitable for the attention of AAVSO observers. Important representatives of the class are sufficiently bright to be readily accessible to small telescopes. These include T Ori, SU Aur, BF Ori, CO Ori, and UX Ori, to mention a few. A more exhaustive list is provided in Herbst *et al.* (1994). The amplitude of variation is often quite large in these stars, sometimes exceeding one or two magnitudes, and the exact cause of the behaviors is still poorly described and understood, as noted above. That said, the simple observation of brightness through a single filter versus time will not do much to advance our understanding of the objects. What is needed is either multiple filters or a coordinated campaign of spectral and photometric monitoring or, ideally, both. To address the opacity issue one needs to know the wavelength dependence of the variations. Small dust grains cause a star to redden as it fades. Gas opacity from hot H gas, for example, has a distinctive spectral signature that includes a sharp break at about 360 nm, where the Balmer continuum begins. This kind of monitoring is clearly for advanced amateurs with a variety of filters and knowledge of CCD reduction techniques. B. Staels (2018) has recently been involved with multicolor monitoring of one of these objects—SU Aur—and has discovered one of the deepest dips ever recorded. There is much fertile ground for exploration here, if one has the advanced capabilities required.

A second kind of project that may interest a wider group of, still advanced, AAVSO observers is checking on PMS stars of all types that have been observed over the decades to see if they are still varying within their known ranges, or whether they have moved outside of those ranges. The actual time scales on which PMS stars change may be rather long compared to human lifetimes or to the time over which we have reasonably accurate records of their brightness. We mentioned above the FU Ori type of accretion variables and an FU Ori-type event could strike any PMS star, without warning. It is important to quantify the occurrence of large accretion outbursts on time scales much longer than has been possible so far. Simply comparing images of star forming clusters (e.g. fields in the Orion nebula and the Taurus dark clouds containing multiple PMS stars) with images taken years ago (e.g. in one of the well-known surveys such as the Palomar Sky Survey, most of which have now been digitized and are available on-line) could be a productive enterprise. Sometimes PMS stars completely change the nature of their variability and such changes may go unnoticed by professional astronomers for a long time. Famous examples include the illumination of a new nebula by a FUOR outburst in a dark cloud in Orion by an amateur astronomer (McNeil *et al.* 2004), long-term changes in the variability of the namesake of PMS variables, T Tau (Beck and Simon 2001), and the dramatic long-term changes exhibited by V582 Mon (Aronow *et al.* 2018). An interesting lesser-known example is CB 34V (Alves *et al.* 1997; Tackett *et al.* 2003) which transitioned from Type III to Type I variability.

One of the challenges for observers of PMS stars is that they are often located in young clusters, which can make it difficult to identify likely non-variable stars to serve as local flux standards. An important new resource, now available on-line to AAVSO observers and, indeed, anyone is the GAIA satellite database from the European Space Agency's (ESA) mission. These data, available at URL: https://www.cosmos.esa.int/gaia, were processed by the Gaia Data Processing and Analysis Consortium (see URL: http://gea.esac.esa.int/archive/). This extraordinary survey of about 1 billion stars provides important basic information including distance, average brightness, and a variability index. With this information one can easily look for non-variable comparison stars that are unlikely, based on their distances, to be PMS members of a young cluster. One can also, of course, find basic information on essentially every star visible on one's CCD image—a real gold mine.

3. Summary

PMS stars remain an attractive possibility for monitoring by advanced AAVSO observers with CCD equipment and knowledge of basic reduction techniques. The easiest thing to do is probably to compare recent images with older, digitized survey images to look for PMS stars that have dramatically changed their brightness levels, as some have been seen to do. Further monitoring of these cases may, then, reveal that they have completely changed the characteristics of their variability. In particular, it would be interesting to improve the statistics on the rare outbursts of FU Ori-type stars. If the Sun and other stars regularly went through such outbursts it could have an impact on our understanding of PMS disk evolution and potentially even relate to features of primitive meteorites that record early times in the solar system. Another area of interest is multi-color photometric campaigns, ideally coordinated with spectral monitoring, to study Type III PMS stars, with the hope of illuminating the cause of their variations.

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