The Variability of Young Stellar Objects

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Abstract A brief review of the types and causes of the variability of young stellar objects (pre-main sequence stars) is given with an emphasis on what we do not yet understand and how amateur observers can continue to make important contributions to the field.

1. Introduction

Alfred H. Joy (1945) was the first to identify a class of eleven irregular variable stars with characteristics similar to his adopted proto-type T Tauri. The amplitude of the variability was large—typically several magnitudes—and irregular, with no evidence of periodicity and no discernible pattern. Some stars behaved erratically, changing brightness by a magnitude or more from night to night, while others were more quiescent. Individual stars went through active periods and quiescent periods, although some could be counted on to generally be more active than others. The close association of these stars with dark and bright nebulosity as well as their spectroscopic characteristics, including emission lines of CaII and HI, indicated that they might be very young stars, an hypothesis more or less proven by George Herbig (1960, 1962). There are now thousands of known T Tauri stars within reach of small telescopes. Many were discovered by their Hα emission and catalogued by Herbig and Bell (1988). Others were found in photometric studies, especially of young clusters such as the Orion Nebula Cluster (Herbst *et al.* 2002).

The range of spectral classes among the original eleven stars of Joy was rather narrow and did not extend later than G5. Today the typical T Tauri star is of K spectral class, while earlier-type counterparts are referred to as Herbig Ae/Be stars. T Tauri stars are the youthful versions of sun-like stars, with masses of a few tenths to a few times the mass of the Sun. Herbig Ae/Be stars are young stars of higher mass. T Tauri stars are further divided into two classes: classical T Tauri stars (CTTS) and weak-lined T Tauri stars (WTTS). The distinction is commonly, although not exclusively, made on the basis of the strength of the Hα emission line. If it exceeds about 10 Å in equivalent width the object is called a CTTS and if it is less than that amount, the object is called a WTTS. Since the strength of the Hα feature is now recognized as a proxy for the star's accretion rate, it is generally the case that CTTS are pre-main sequence stars that are still accreting from surrounding disks, while WTTS are only weakly accreting from their disks, if at all. We have learned that the presence or absence of an accretion disk is in fact the most important determinant of the observed characteristics of a young star, including the type of variability it exhibits.

2. The evolutionary status and structure of young stellar objects

2.1. Pre-main sequence stars

Stars form from interstellar clouds of gas and dust when parts of them become dense enough and cold enough that gravity overcomes random thermal motions and initiates the inexorable collapse that leads to a star. During this time, the radius of the sphere of matter that will become a star decreases by about a million fold! At the center, there quickly accumulates a protostar that is transforming the infalling energy of the accreting gas into thermal energy as it crashes into the central sphere. Within a hundred thousand years (or less for more massive stars) the central object has reached stellar temperatures at its surface, but is not quite hot enough at its center to initiate nuclear burning of Hydrogen. Such stars are easily visible, nonetheless, and make up the general class of variable stars known as young stellar objects discussed here. They are also referred to as pre-main sequence stars because they have not yet fully contracted to their main sequence size, where they will stabilize as their cores become hot enough to initiate the H-burning needed to stop the collapse. Pre-main sequence stars shine primarily by slowly shrinking, thereby converting gravitational potential energy to thermal energy, some of which is radiated away. It takes about 30 My for a sun-like star to reach the main sequence and finally turn on its core nuclear burning, but its T Tauri phase is much shorter than that, only the 1–10 My it takes to dissipate its accretion disk and organized surface magnetic fields. Older pre-main sequence stars are sometimes called post T Tauri stars (PTTS) and show little variability at optical wavelengths although they may still be strong X-ray sources.

2.2. Accretion disks

Anything that collapses by a million-fold will also spin up by a huge factor due to the well known phenomenon of conservation of angular momentum. A skater who brings her arms in close to her body spins noticeably faster even though the contraction in distance is only a few times, not a million times! It is not hard to show that even the slightest amount of spin expected to be present in an initial cloud would produce a protostar spinning faster than the speed of light if angular momentum were conserved. Exactly how forming stars rid themselves of this excess spin energy is complicated and unknown in detail, but it is clear that two things often result. First, binary stars are a common outcome of the star formation process and they can store a good deal of angular momentum in the orbital motion of the stars. A second common outcome is a single star with planetary system—again a good sink for angular momentum. Note that it is also possible and presumably common to have a binary system with planets, as recent observations with the Kepler satellite have demonstrated. Prior to forming individual planets, the systems collapse to a central pre-main sequence star (or binary) plus a disk. Spectacular Hubble Space Telescope images of the Orion Nebula Cluster, for example, have revealed these disks around many of the young stellar objects in that cosmic nursery.

Rapid rotation has a flattening effect on matter, as anyone who has watched pizza dough spun into a crust will recognize. Disks probably form around every young star although some may be disrupted by interactions with binary companions or neighboring stars within a cluster. The great success of the Kepler mission at finding planets shows that disks survive in most cases and planets form within them. Initially, however, the disks are primarily gaseous and have a viscosity that causes some matter to be driven inward towards the star. As the accreting matter reaches a distance of only a few stellar radii it encounters the star's magnetosphere, a region dominated by intense magnetic fields rooted at the stellar magnetic poles. Some of the incoming matter is caught in the rotating fields and ejected perpendicular to the disk, forming bipolar jets of outflowing material. The rest is funneled to the star's surface in the polar regions much like the solar wind is funneled into auroral rings on Earth (Hartmann 2001).

Figures 1 and 2 show the structure of a CTTS and a WTTS. In the CTTS the disk is more massive, composed of mostly gas and is still accreting onto the star, causing the irregular, large amplitude variability first noticed by Joy. In the WTTS there is still a disk, since planets have not yet formed, but the gas is largely gone and there is little or no accretion. Since the star still has a very strong surface magnetic field it still exhibits some variability due especially to its rotation and the presence of dark spots. A PTTS probably looks much like a WTTS except that the magnetic field has weakened or become more irregular so that the spots are more uniformly distributed around the star, resulting in less photometric variability.

3. Variability types among young stellar objects

While many different classification schemes have been used to characterize the sometimes bewildering observed phenomena, here we will follow the scheme proposed by Herbst *et al.* (1994) augmented by two types of eruptive variable described originally by George Herbig and a potential new form of variability signified by the unique behavior of KH 15D.

3.1. Periodic variables with cool spots (type I variables)

Most WTTS show regular, often nearly sinusoidal, variations of 0.1 to 0.3 magnitude in their optical light on time scales of 1 to 15 days. The largest amplitude example is V410 Tau (Herbst 1989). The shapes and amplitudes of these variations typically evolve on timescales of months or years but the periods remain stable, supporting the view that the cause of the variation is the rotation of a cool spotted surface. For many beautiful examples of such light curves see Grankin *et al.* (2008). The scientific interest in these stars is that they provide a handy and reliable method to measure the rotation period of pre-main sequence stars. They are not an easy target for amateurs since they tend to be relatively faint stars with fairly small amplitude variations. For advanced amateurs with CCDs who wish to commit many months of rather continuous observing time (they require nightly or even hourly observation) and can deal with the analysis issues (normally the period is only revealed by a rather sophisticated mathematical analysis such as a Fourier transform) the payoff is a rotation period for a young star. We now have such periods for thousands of young stars so the incremental value of another one is not so great. But there may still be interesting objects out there and the possibility of changing periods, perhaps caused by differential rotation on the surface of the star, as occurs on the Sun, remains open.

3.2. Mostly irregular variables with hot spots (type II variables)

Most CTTS show this kind of variability due to the irregular nature of the accretion heating. Just as auroral displays wax and wane with the solar wind, the brightness of CTTSs wax and wane irregularly with accretion rate changes. While interesting, it is hard to get too much useful science out of these changes which can be like trying to understand the comings and goings of clouds! But there are some interesting projects for amateurs here and some new techniques for extracting useful information (Percy *et al.* 2010a, b). The prototype for these stars is T Tauri itself and it had a sufifciently stable variation during one epoch of observation that we were able to determine its rotation period of 2.8 days (Herbst *et al.* 1986, 1987). This work was done with the collaboration of many astronomers including amateurs because we needed data to be obtained at many different longitudes. There are undoubtedly more CTTS that will show periodicity when enough data are accumulated on them.

On the longer term, the modulation of the irregular behavior in these stars is very interesting and something that AAVSO observers have contributed to and can continue to contribute to. For example, T Tauri has a very extensive data base in the AAVSO archives that shows it has gone through periods of great activity and periods of relative quiescence. The cause of these modulations is unknown but could have to do with companions orbiting it (Beck *et al.* 2001), either stars or perhaps protoplanets. Continuing to keep an eye on this object and similar ones is a task well suited to the AAVSO and of potentially great scientific importance, especially should some unexpected behavior occur.

3.3. Irregular variables suffering occultations (type III variables): UXors

Many Herbig Ae/Be stars and earlier type CTTS such as RY Tau and CO Ori undergo this type of variability. While its cause is still debated, it seems clear that these stars are irregularly occulted by circumstellar matter. The timescales are similar to, although perhaps a bit longer than, the Type II variables and there is probably a mixture of accretion-related heating and occultation going on in some sources. One characteristic of the class is that there can be rather sudden drops in the brightness of the star by one, two, or even three magnitudes followed by slower and often irregular recoveries. When very faint the stars are bluer and more polarized, indicating that scattered light by small grains is important (Voshchinnikov *et al.* 1988). A possible cause of the variations is obscuration of the photosphere by dusty accreting material. The interesting periodic star AA Tau may be of this type but apparently has the property that the occulting matter is confined to a warped disk rather than an accretion stream, leading to its periodicity (Bouvier *et al.* 1999, 2003). Alencar *et al.* (2010) have noted a number of AA Tau-like stars in young clusters that may be UXors. The prototype for the class is UX Orionis, hence the name.

The UXors probably represent the only major class of variable stars in which the exact mechanism of variability is still debated. As such they deserve all the observational attention they can get. The long records of the AAVSO are very important for understanding these variables and how they evolve. Since the occulting matter may, in some cases, be solids within protoplanetary disks there may be encoded in the variability information about the early stages of the formation of planets. As is often the case, data on these stars are of considerably more value if they are obtained at more than one wavelength. This allows astronomers to determine the optical properties of the occulting material, in particular whether it is the very small grains characteristic of the interstellar medium or larger solids expected to grow within disks during the first stages of planet formation. Many light curves of UXors can be seen in the paper by Herbst and Shevchenko (1999).

3.4. Large scale eruptive variables (FU Orionis stars): FUors

A few T Tauri stars are known to have gone through substantial eruptive events in which they brighten by several magnitudes and maintain their bright state for months or years. Their prototype is FU Orionis and the class was first proposed and discussed by Herbig (1977). While debate continues about the exact causes of this phenomenon it appears to be related to a rather abrupt increase in the accretion rate (Hartmann and Kenyon 1996). Such eruptive behavior in pre-main sequence stars, if common, could have substantial effects on forming planets, since the increased luminosity of the star would heat disk material well above what would be typical for a non-erupting T Tauri star.

The field of eruptive pre-main sequence stars is one which has benefitted from the participation of amateur astronomers and may continue to do so. Amateur astronomer J. McNeil discovered a new nebula that was produced as a result of a likely FUor outburst in 2004 (McNeil *et al.* 2004; Briceno *et al.* 2004). Regular patrolling observations of star forming regions may reveal such eruptions well before they are noticed by professional astronomers. It is interesting that most, if not all, FUors are found in relatively isolated star forming locales, not within the denser regions of the populous clusters such as the Orion Nebula Cluster, IC 348, and NGC 2264 where many professional survey programs are concentrated. The statistics of the FUor phenomenon are quite uncertain owing to the small number of definitive cases. This makes it difficult to assess how important the phenomenon is to star and planet formation in general.

3.5. Small scale eruptive variables (EX Lupi stars): EXors

Herbig (2007) described the behavior of another rather large amplitude T Tauri variable, EX Lup, and suggested it may represent a class of eruptive variables with similarity to the FUors but on a smaller scale. Unfortunately the class remains rather heterogeneous and ill-defined (Herbig 2008). Presumably these are stars also suffering enhanced accretion events but not to the extent of the FUors. It is unclear at present whether these are just extreme examples of the Type II variability characteristic of most CTTS or represent something distinctly different and perhaps related to the FUor phenomenon. Again, improving the statistics of light curve behavior among these large amplitude CTTS, especially ones that are not concentrated into the massive clusters that professionals prefer to monitor, is a field in which amateur astronomers could make major contributions.

3.6. Periodic variables of KH 15D type

Kearns and Herbst (1998) described a large amplitude, strictly periodic variable now known as KH 15D, in NGC 2264. Its behavior is unique and now understood as arising from a binary T Tauri star with a warped, precessing circumbinary disk (Chiang and Murray-Clay 2004; Winn *et al.* 2004; Hamilton *et al.* 2005). Other large amplitude, strictly periodic variables have been found that may, like KH 15D, be caused by circumstellar matter within a disk periodically occulting a single star or one member of a binary. Possible members of this class include V718 Per (HMW 15) (Grinin *et al.* 2008) and CHS7797 (Ledesma *et al.* 2012). AA Tau (Bouvier *et al.* 1999, 2003) also may meet this definition, perhaps creating a bridge to the aperiodic UXors. In any event, the discovery of additional cases of large amplitude, periodic occultations would be very interesting. Since most of the stars in this class appear to exhibit the periodicity only episodically, this is another area in which careful, long-term monitoring programs such as amateurs can carry out under the auspices of the AAVSO may yield substantial scientific payoffs.

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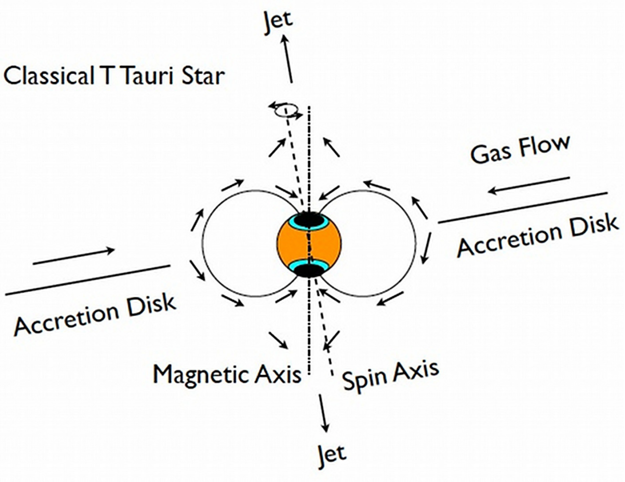

Figure 1. Schematic diagram of a CTTS showing the gas flows through the accretion disk and then into the jet or onto the star near the magnetic pole. The dark spots at the poles result from disruption of convective energy transport by the magnetic field, just like in sunspots. The bright rings around them represent parts of the photosphere heated by the accreting gas and are analogous to auroral rings on Earth. The small misalignment of the rotation and magnetic axes leads to periodic variability of the star as we view different parts of its inhomogeneous surface.

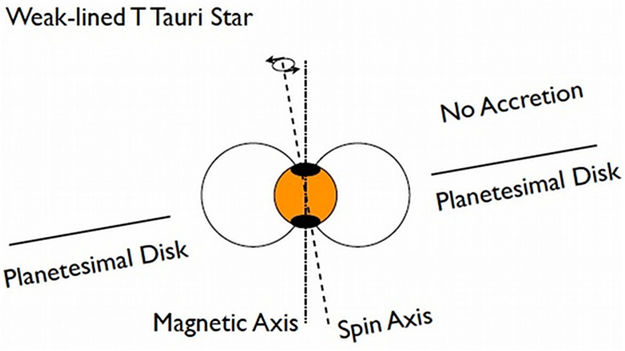

Figure 2. Schematic diagram of a WTTS showing that there is now little, if any, gas flow through the disk or accretion onto the star. Much of the irregular variability therefore disappears in these stars but they continue to show periodic variations of typically 0.1–0.3 mag. caused by the rotation of their spotted surfaces. For WTTS it is often possible to determine their rotation period since the surface spot distributions often remain stable for months or even years.