201. Young stellar objects

YOUNG STELLAR OBJECTS (YSOs) represent the earliest stages of star formation. The term embraces the *protostar* phase, which starts with the gravitational collapse from the parent molecular cloud (lasting of order 0.5 Myr while the object is still accumulating mass), and the subsequent *pre-main-sequence* phase (PMS), which starts with the exhaustion of the infalling gas.

The PMS phase continues until contraction, and the associated temperature increase, initiates H fusion. Residual gas and dust is blown away, the object becomes visible optically, and the star settles onto the zero-age main-sequence (ZAMS). As the disk material is depleted, its infrared emission decreases, such that YSOs can be classified in evolutionary stages based on their infrared spectral index (classes I, II and III due to Lada, 1987).

Pre-main-sequence stars are classified by mass as T Tauri stars ($M \lesssim 2M_\odot$, with ages $\lesssim 10$ Myr; Joy, 1945), or Herbig Ae/Be stars ($2-8M_\odot$; Herbig, 1960; Thé et al., 1994), with more massive stars contracting too rapidly to be visible as PMS objects.

YSOs are associated with many other early evolutionary phenomena and phases (e.g. Lada, 1985): circumstellar and protoplanetary (proplyd) disks, jets and bipolar outflows, masers, Herbig–Haro objects (associated nebulosity), and dippers, as well as the episodically accreting FU Ori and EX Lup (aka EXor) variables.

So far, I have mentioned some of these phenomena only in passing: YSOs in molecular clouds (essay #192) and wide binaries (193); and T Tauri stars in the context of OB associations (18) and stellar rotation (103).

HIPPARCOS made a contribution to the field by providing direct distance estimates to a number of star-forming regions and individual YSOs, including both T Tauri (e.g. Frink et al., 1998; Hoff et al., 1998; Wichmann et al., 1998), and Herbig Ae/Be stars (e.g. van den Ancker et al., 1998; Vieira et al., 2003), and better identifying their location with respect to the main sequence, and the predictions of evolutionary models.

A catalogue of 1250 proper motions, allowing their origins to be traced back in time to sites of star formation, was given by Ducourant et al. (2005).

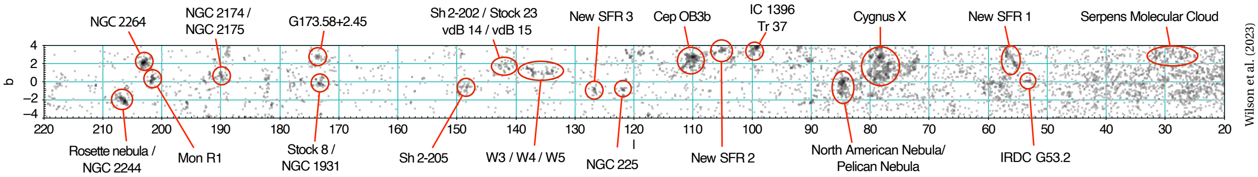
THE FIRST large-scale application of the Gaia data to the identification of YSOs came with a study using DR2 by Marton et al. (2019). They constructed a cross-matched catalogue of 103 million objects from Gaia and WISE (in the infrared), and used machine learning to assign each object to four classes: YSOs, main-sequence, evolved stars, and extragalactic objects. This yielded 1.1 million YSO candidates at 90% probability.

For verification, they showed that the 3D structure of the Orion A star-forming complex agreed with the recent literature. They also assessed the efficiency of the Gaia Science Alerts pipeline (essay 36) in detecting rapid YSO brightness changes caused by episodic accretion. As of 2019 April, the Gaia Alerts database included 7 670 objects, of which 131 were known to be YSOs. Finding 187 YSOs in their DR2–WISE sample suggests that even more of the alerts are attributable to YSO activity. I will return to this in the context of FU Ori and EXor variables below.

WITH GAIA DR3, the Konkoly Catalogue of 12 000 optically selected YSOs within 2 kpc (KYSO, Marton et al., 2023), based the *Handbook of Star Forming Regions* (Reipurth, 2008a; 2008b), was created as a training set for the DR3 variability processing. The classification of 12.4 million DR3 variables into 25 classes, including the class of YSOs, is detailed by Rimoldini et al. (2023).

Their analysis (their §4.24) yielded 79 375 YSOs of various classified sub-types, including dipper stars (DIP), eruptives such as FU Ori-type variables (FUOR), pulsating PMS stars (PULS_PMS), Herbig Ae/Be types (HAEBE), and T Tauri star (TTS), among which are classical (CTTS), weak-lined (WTTS), and late G to early K type pre-main-sequence (GTTS) stars. Some 40 000 of these had not been previously catalogued as YSOs.

Given the relatively low completeness and high contamination expected for optical observations alone, detailed validation by comparison with numerous literature catalogues was carried out by Marton et al. (2023). They found that most candidates are indeed found along lines-of-sight to known star-forming regions and the Galactic mid-plane, with an average of 10% contamination, and completeness at around the percent level.



An ADS search returns some 130 refereed papers on Gaia–YSO studies to mid-2024, and the following gives a flavour of the many ongoing investigations.

The largest catalogue of mid-infrared (3–9 μm) YSOs in the Galactic plane is from the Spitzer–IRAC wide-area mapping. In their study of 120 000 of these YSO candidates, Kuhn et al. (2021) used DR2 distances to associate these YSOs with the Local Arm, the Sagittarius–Carina Arm, and the Scutum–Centaurus Arm.

In an extensive classification exercise using a 'naive Bayes classifier', and data from WISE, UKIDSS, 2MASS and IGAPS, along with photometric variability from Gaia EDR3, Wilson et al. (2023) identified 6504 candidate Class II YSOs, with good sensitivity to different evolutionary stages (see figure above).

Between the end of the AGB phase and the onset of the planetary nebula phase, the AGB dust shell becomes optically thin, resulting in infrared colours similar to those of YSOs because of their similar cold, dense circumstellar dust envelopes. With YSOs and AGB stars commonly identified from their infrared 2-colour diagrams (e.g., Koenig & Leisawitz, 2014; Suh, 2021), misclassification can arise in the significant overlap regions (e.g. Lee et al., 2021). Suh (2024) showed that distance and extinction data from Gaia DR3 is highly effective in distinguishing these very different stellar classes.

Amongst studies of YSOs in specific star-forming regions, Grasser et al. (2021) used the 3D data from Gaia EDR3 of the ρ Oph region to evaluate the existing catalogue of 1114 YSO members from the literature. They found 191 new YSOs (mainly Class III M stars). The proper motions reveal two distinct populations in a similar 3D volume (and 17 non-members): one around ρ Ophiuchi and the main Ophiuchus clouds, and the other ~10 Myr older, more dispersed, and possibly from the Upper Sco group.

Using DR3, Narang et al. (2023) searched for optical counterparts for 62 protostars in Orion, and Gómez de Castro et al. (2024) characterised 63 candidate T Tauri stars in the Taurus–Auriga molecular complex.

Gaia parallaxes and proper motions are also being used to study young stars in the regions of Herbig Haro objects and flows, for example in Canis Major (Pettersson & Reipurth, 2019); around the BBWo 192E nebula (Magakian et al., 2020); in the Dobashi 5006 Dark Cloud (Movsessian et al., 2023); and in the Taurus B18 cloud (Duan et al., 2023).

The FU Ori variables are PMS stars displaying abrupt changes in magnitude and spectral type. The prototype, FU Ori, increased from 16.5 to 9.6 mag in 1937. The second, V1057 Cyg, brightened by 6 mag and transitioned from dKe to F-type in 1969–70 (Kopatskaya et al., 2013). The flaring appears to be repetitive, cycling between the FUor state and the T Tauri state (Reipurth, 1990). Amongst various models (Audard et al., 2014; Vorobyov et al., 2021) are episodic mass transfer from an accretion disk (Vorobyov & Basu, 2006; Vorobyov & Basu, 2015), or possibly due to a young, inwardly migrating gas giant planet (Lodato & Clarke, 2004; Nayakshin & Lodato, 2012; Nayakshin & Elbakyan, 2024).

Even 50 years ago, the mean time between FU Ori-type outbursts in individual T Tauri stars had been estimated at 10 000 years (Herbig, 1977). Contreras Peña et al. (2019) have further quantified this rate by comparing old photographic surveys with Gaia DR2, giving a temporal baseline of 55 yr for 15 000 Class II objects. They found 139 with $\Delta R \geq 1$ mag (mostly 1–3 mag), most showing irregular variability or long fading events, best explained as hotspots due to accretion or variable extinction. A tail at $\Delta R \geq 3$ mag showed high-amplitude irregular variability over time-scales shorter than 10 yr.

Six objects were consistent with large, long-lasting accretion events, 3 previously unknown. This yielded a recurrence time-scale of 112^{+68}_{-38} kyr, and confirms that YSOs in their planet-forming stage undergo such large accretion events. Outbursts in the Class II stage are a factor ten less frequent than Class I.

Pre-Gaia, around 10 FU Ori stars were known. Gaia is discovering others with ongoing flares from its Science Alerts pipeline, including Gaia 17bpi (Hillenbrand et al., 2018), Gaia 18dvy (Szegedi-Elek et al., 2020), and Gaia 19ajj (Hillenbrand et al., 2019).

The related class of EXors, named after the prototype EX Lupi, are indistinguishable from T Tauri stars apart from repeated luminosity increases, a year or so in duration, attributed to episodic accretion (Herbig, 2008; Sipos et al., 2009; Lorenzetti et al., 2012; Moody & Stahler, 2017; Magakian et al., 2023).

Again, others are being discovered through the Gaia Science Alerts pipeline, and characterised by Gaia astrometry. They include Gaia19fct (Park et al., 2022; Ghosh et al., 2022), Gaia20eae (Cruz-Sáenz de Miera et al., 2022), Gaia21elv (Nagy et al., 2023), Gaia21bty (Siwak et al., 2023), and Gaia23bab (Giannini et al., 2024).