PHYSICAL SCIENCES

PHOTOMETRİC AND SPECTROSCOPİC VARİABİLİTY İN HERBİG STARS

Huseynova F.
PhD candidate, Batabat Astrophysical Observatory,
Nakhchivan State University, Azerbaijan
https://orcid.org/0009-0009-3765-2292
Mammadli A.
Associate professor, Batabat Astrophysical Observatory,
Nakhchivan State University, Azerbaijan
https://orcid.org/0009-0007-9819-3961
https://doi.org/10.5281/zenodo.18631251

Abstract

The article explain the majority of Herbig stars are in binaries (≳ 70%). The mass ratios of the binary Herbig stars indicates that the binaries form from disk fragmentation. Given that many of these are unresolved at arcsecond resolution, this also has important implications for interpreting the X-ray properties of Herbig stars.

Herbig stars display photometric and spectroscopic changes on timescales ranging from hours to months and longer. The larger amplitude photometric changes can be traced back to variable dust obscuration from an orbiting disk, while variability at smaller, milli-magnitude, amplitudes can be analyzed with asteroseismology. Spectroscopically, variable line emission is mostly associated with the accretion process, while variable absorption lines can be due to changes in the accretion process itself, but can also be caused by infalling rocky material such as exo-comets.

Keywords: spectroscopic, photometric, intermediate-mass stars, variability.

Introduction

Over the last twenty-five years, interferometric observations at millimeter wavelengths of gas emission from disks surrounding young stars have allowed astronomers to determine the dynamical masses of these young stars [3, 14, 19, 21, 22]. The Atacama Large Millimeter Array (ALMA), with its high spatial resolution and sensitivity, has enabled the measurement of increasingly large samples of dynamical masses. These measurements serve as a critical benchmark for testing stellar evolution models and, consequently, the ages and masses derived from them. Braun et al. [3] assembled the most extensive such sample to date and reported that, for stars with model-inferred masses between 1.3 and 3.0 $M_{\odot}$, the evolution models predict masses that are systematically lower than the dynamically measured masses by approximately 5% to 14%.

It can be informative to examine Herbig stars within the context of their locations on the Hertzsprung-Russell (HR) diagram. Vioque et al. [24] plotted 218 known and candidate Herbig stars with precise Gaia DR2 parallaxes [5] on the HR diagram; a version of this plot is shown in Figure 1. For reference, several theoretical evolutionary tracks and isochrones are overlaid. As anticipated, most Herbig stars are located at or above the Zero-Age Main Sequence (ZAMS), indicating that intermediate-mass stars typically stop accreting material shortly before or soon after reaching the ZAMS. Herbig Be stars, which are more massive, are less numerous than Herbig Ae stars – a trend consistent with both the Initial Mass Function and the shorter evolutionary timescales associated with higher-mass stars as they approach the Main Sequence.

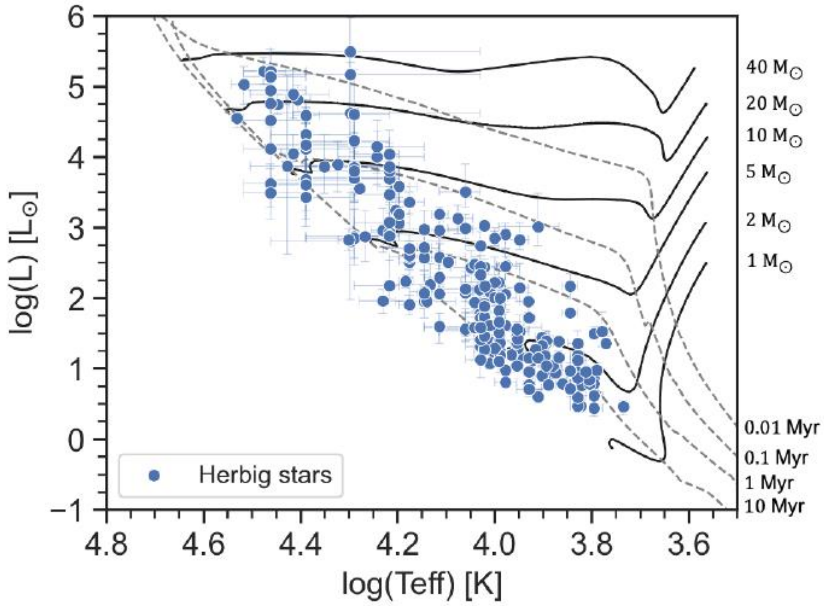

Fig. 1. *HR diagram containing 218 Herbig stars with high quality DR2 Gaia parallaxes (adapted from Vioque et al. (2018), their Figure 2).*

Higher-mass Herbig stars are consistently younger than their lower-mass counterparts (see Figure 2). The ages of the lower-mass Herbig stars generally span from a few million years up to around 10 million years. These older age estimates have important implications for the evolution and longevity of their circumstellar disks, a topic that will be addressed following a summary of the stellar properties.

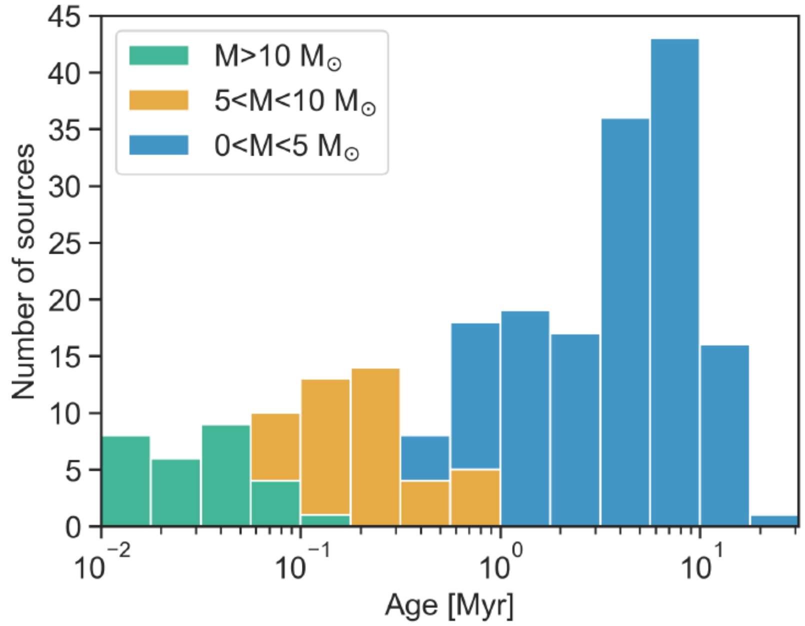

Fig. 2. *The age distribution of the 218 Herbig stars (Vioque et al. 2018). As shown in the diagram, the highest-mass stars have the smallest ages. Most Herbig Ae stars, and thus their disks, are older than several million years.*

Binaries among Herbig stars

Herbig stars are predominately found in binary systems, and many of these are found at arcsecond scales. Leinert et al. [16] and Pirzkal et al. [18], both investigations found a binary frequency of approximately 70% within this parameter range, with a suggestion that Herbig Be stars have a higher tendency to exist in binary systems. Wheelwright et al. [25] managed to spectroscopically resolve some previously undetected binaries and concluded that their mass ratios are near unity. This finding is inconsistent with random pairing from the Initial Mass Function (IMF), which would be expected if stellar capture were the dominant binary formation pathway. The same research group later reported in Wheelwright et al. [25] that the alignment between the binary components and the disks around the primary stars supported disk fragmentation as the likely formation mechanism.

Similar arguments in favor of fragmentation as the origin of Herbig binaries were advanced by Arun et al. [1], who announced the discovery of a widely separated

(6.6″) Herbig Ae–M star binary. Given the large separation, fragmentation at an earlier evolutionary stage was considered the most plausible scenario.

Surveys conducted with the Very Large Telescope Interferometer (VLTI) by Lazareff et al. [15, observing in the H-band with 51 targets] explored smaller orbital separations with contrast sensitivities comparable to earlier studies. These surveys resulted in few companion detections. However, it should be noted that the target selection was biased against known radial-velocity binaries, as the observations were primarily designed to study circumstellar disks. Despite this, milli-arcsecond Herbig Be binaries, corresponding to physical separations below 500 AU, have been detected using VLTI data [12, 13].

Finally, the smallest separation regimes can be investigated spectroscopically, either by detecting radial velocity variations or by directly observing double-lined spectroscopic binaries. There has been limited work in this area, with the spectroscopic survey of 42 Herbig stars by Corporon & Lagrange [6] remaining the largest dedicated study to date. This latter category includes spatially resolved objects with known separations around 0.5″; consequently, the observed close binary fraction based solely on radial velocity variations stands at 17%.

Photometric variability

Herbig stars exhibit distinct photometric variability across different wavelengths, providing key insights into their circumstellar environments. Studies have documented large, non-periodic optical brightness variations reaching up to $\Delta V \sim 3$ mag [10]. A defining phenomenon, known as UXor variability, was characterized through detailed observations of the star UX Ori. This behavior involves an initial reddening as the star fades, followed by a reversal to a bluer color during deep minima – the "blueing effect" [2, 11]. Concurrent increases in polarization indicate scattering by circumstellar dust. Multi-technique observations [8, 9] support a model where this effect is caused by opaque dust clouds in the inner disk transiting the line of sight.

In contrast, near-infrared (NIR) variability is significantly more subdued. Quasi-simultaneous optical and NIR monitoring of Herbig Ae stars by Eiroa et al. [7] revealed optical variations up to 0.5 mag, compared to typical NIR variations of only ~0.1 mag. For most objects in their sample, the optical and NIR variations were correlated, linking the origin of NIR variability to thermal re-emission from hot dust in the inner disk. The star UX Ori itself was an exception, showing no such correlation, which was attributed to rotational modulation from starspots. Subsequent analysis by Vioque et al. [24] estimated that roughly 25% of Herbig stars exhibit UXor-like variations, with Herbig Be stars being notably less variable.

Furthermore, high-precision space-based photometry has enabled the detection of low-amplitude, millimagnitude pulsations in some Herbig Ae stars [4, 26, 27, see compilation by [23]]. These pulsations are identified as δ Scuti-type variability [20], originating from radial oscillations in stars located within the classical instability strip. This milli-magnitude variability opens the door to asteroseismology of pre-main-sequence stars. A prominent example is HD 139614, for which asteroseismic modeling yielded an age of about 11 Myr [17]. This relatively old age confirms that gas-rich circumstellar disks can persist for substantial periods.

Spectroscopic variability

Herbig stars exhibit variability not only in their brightness but also in their spectral emission lines. Studies indicate that variations in the strength and shape of these emission lines are linked to the rotation of the star, which periodically brings the regions of mass accretion in and out of view. This type of variability is generally less pronounced in Herbig stars than in younger T Tauri stars, where the accretion process is more strongly influenced by magnetic fields.

Research focusing on larger samples, particularly monitoring the Hα emission line, shows that variability occurs across a wide range of timescales. The amplitude of change grows from very short timescales (minutes) to longer ones (days to weeks), and can be observed even over several years. This pattern suggests the changes originate in a compact region close to the star and are primarily driven by fluctuations in the rate at which material accretes onto the stellar surface. Therefore, emission line variability serves as a key indicator of ongoing accretion in these systems.

Another distinct form of spectroscopic variability involves transient absorption features from metals. In this phenomenon, absorption lines can appear suddenly and become progressively more red-shifted over just a few hours. This signature is interpreted as evidence for gas released from evaporating, comet-like bodies falling onto the star. Observations show that a significant proportion of Herbig stars display this behavior, linking it to the presence of solid bodies within their disks. This spectral signature is considered an indirect method for detecting the building blocks, or possibly even planets, within these circumstellar environments.

Conclusion

This study underscores the complex and dynamic nature of Herbig stars. Photometric and spectroscopic observations point to both dust clouds in the circumstellar disk and instabilities in the accretion process as primary drivers of their variability. Furthermore, the high frequency of binary systems among these stars and their near-unity mass ratios highlight the dominant role of disk fragmentation in their formation. Finally, the observed relatively long (several million years) active disk phase in these stars confirms the presence of a prolonged and dynamic environment for planet formation around intermediate-mass stars. Future high-resolution and long-term monitoring studies will provide deeper insight into the processes of accretion, obscuration, and material dynamics occurring in these young stellar systems.

References:

1. Arun, A., Haque, M. M., Washington, S., et al. (2021). A systematic review of traffic conflict-based safety measures with a focus on application context. Analytic methods in accident research, 32, 100185.

2. Bibo, E. A., The, P. S. (1990). A study of the Herbig Ae-type star UX Orionis: its remarkable behavior in the colour-magnitude diagram, and the properties of its dust shell. A&A, 236, p.155.

3. Braun, V., Clarke, V., Boulton, E., et al. (2021). The online survey as a qualitative research tool. International journal of social research methodology, 24(6), p.641-654.

4. Casey, M. P., Zwintz, K., Guenther, D. B., et al. (2013). MOST observations of the Herbig Ae δ-Scuti star HD 34282. Monthly Notices of the Royal Astronomical Society, 428(3), p.2596-2604.

5. Collaboration, G., Mignard, F., Klioner, S. A., et al. (2018). Gaia Data Release 2. A&A, 616, p.14.

6. Corporon, P., Lagrange, A. M. (1999). A search for spectroscopic binaries among Herbig Ae/Be stars. Astron. Astrophys. Suppl. Ser., 136, p.429-444.

7. Eiroa, C., Oudmaijer, R. D., Davies, J. K., et al. (2002). On the simultaneous optical and near-infrared variability of pre-main sequence stars. A&A, 384, p.1038-1049.

8. Grinin, V. P., The, P. S., de Winter, D., et al. (1994). The β Pictoris phenomenon among young stars. I. The case of the Herbig AE star UX Orionis. A&A, 292, p.165-174.

9. Grinin, V. P. (1992). Young stars with non-periodic Algol-type minima. Astronomical and Astrophysical Transactions, 3, p.17-32.

10. Herbst, W., Herbst, D., Grossman, E. J., et al. (1994). Catalogue of UBVRI photometry of T Tauri stars and analysis of the causes of their variability. Astrophys. J., 108, 1906-1923.

11. Huseynova, F. S., Ismayilov, N. Z., Alishov. S. A. (2025). Photometric and Spectral Study of the Star AS 442. Young Researcher Scientific & practical journal, Cild XI, №3, p. 90-100.

12. Koumpia, E., de Wit, W. J., Oudmaijer, R. D., et al. (2021). The first interferometric survey of massive YSOs in the K-band-hot dust, ionised gas, and binarity at au scales. Astronomy & Astrophysics, 654, p.109.

13. Kraus, M., Liimets, T., Cappa, C. E., et al. (2017). Resolving the circumstellar environment of the Galactic B [e] supergiant star MWC 137 from large to small scales. The Astronomical Journal, 154(5), p.186.

14. Law, A. M. (2022). How to build valid and credible simulation models. In 2022 Winter, Simulation Conference (WSC) p.1283-1295

15. Lazareff, B., Berger, J. P., Kluska, J., et al. (2017). Structure of herbig aebe disks at the milliarcsecond scale-a statistical survey in the h band using pionier-vlti. Astronomy & Astrophysics, 599, p.85.

16. Leinert, C., Bowyer, S., Haikala, L. K., et al. (1998). The 1997 reference of diffuse night sky brightness. Astronomy and Astrophysics Supplement Series, 127(1), p.1-99.

17. Murphy, S. J., Joyce, M., Bedding, T. R.,(2021). A precise asteroseismic age and metallicity for HD 139614: a pre-main-sequence star with a protoplanetary disc in Upper Centaurus–Lupus. Monthly Notices of the Royal Astronomical Society, 502(2), p.1633-1646.

18. Pirzkal, N., Spillar, E. J., Dyck, H. M. (1997). A Search for close bright companions to AeBe Stars. ApJ, 481, p.392-395.

19. Rabeony, H., Petit-Paris, I., Garnier, J., et al. (2014). Inhibition of keratinocyte differentiation by the synergistic effect of IL-17A, IL-22, IL-1α, TNFα and oncostatin M. PloS one, 9(7), e101937.

20. Ripepi, V., Cioni, M. R. L., Moretti, M. I., et al. (2017). The VMC survey–XXV. The 3D structure of the Small Magellanic Cloud from Classical Cepheids. Monthly Notices of the Royal Astronomical Society, 472(1), p.808-827.

21. Simon, M., Houghton, S. M., Aquino, K. (2000). Cognitive biases, risk perception, and venture formation: How individuals decide to start companies. Journal of business venturing, 15(2), p.113-134.

22. Simon, T., Hero, B., Schulte, J. H., et al. (2017). 2017 GPOH guidelines for diagnosis and treatment of patients with neuroblastic tumors. Klinische Pädiatrie, 229(03), p.147-167.

23. Steindl, T., Zwintz, K., Barnes, T. G., et al. (2021). Pulsational instability of pre-main-sequence models from accreting protostars-I. Constraining the input physics for accretion with spectroscopic parameters and stellar pulsations. Astronomy & Astrophysics, 654, p.32.

24. Vioque, M., Oudmaijer, R. D., Baines, D., et al. (2018). Gaia DR2 study of Herbig Ae/Be stars. A&A, 620, p.17.

25. Wheelwright, S. J., Sadek, S. A., Baron-Cohen, S., et al. (2011). A behavioral comparison of male and female adults with high functioning autism spectrum conditions. PloS one, 6(6), e20835.

26. Zwintz, K., Fossati, L., Ryabchikova, T., et al. (2014). Echography of young stars reveals their evolution. Science, 345(6196), p.550-553.

27. Zwintz, K., Kallinger, T., Guenther, D. B., et al. (2009). MOST photometry of the enigmatic PMS pulsator HD 142666. Astronomy & Astrophysics, 494(3), p.1031-1040.