Visible and IR Light Curve Variability Analysis of Young Stellar Objects in IC417

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Abstract

The Spider Nebula (IC417) is a star-forming region ~2.3 kpc away towards the Galactic anticenter. We have identified 710 young stellar object candidates (YSOc) in this region based on the literature (IR excess from WISE or Spitzer/IRAC-1/2, Halpha excess, variability, or identification as O/B stars) or on our own identification based on position in the Nebulous Stream (NS; Jose et al. 2008); see our companion poster Urbanowski et al.

In this work, we continue exploration of these YSOc by investigating their variability properties, where possible, in the optical (via Zwicky Transient Facility, ZTF) and in the IR (via NEOWISE) on timescales of days to thousands of days. Of the 512 YSO candidates identified by us as fairly confident YSOc, 367 have ZTF light curves (LC) in either g or r band, and 272 have NEOWISE LC in either W1 or W2.

Approach

- We assembled a list of YSOc in this region from the literature, plus all the IR-bright stars within the NS; see our companion poster. Of the 710 YSOc found there, we regard 512 as highly likely to be YSOs.
- For each of those 512, we looked for light curves (LCs) with >100 points in ZTF r and/or g, or in NEOWISE W1 and/or W2. Of the 512, we found LCs for 420 targets (367 ZTF; 272 NEOWISE).
- To look for variables, we started by calculating chi-squared (χ^2), comparing to a flat light curve. By assessing the distributions of χ^2 for the ensemble of LCs, we took as variables those LCs with χ^2 >4 in ZTF and χ^2 >5 in NEOWISE, leaving 254 variables (193 ZTF; 160 NEOWISE). About 53% are variable in the optical, and ~59% are variable in the IR.
- We have begun searching for periods via Lomb-Scargle, but few stars appear to be periodic. We have matched pairs of bands obtained within 12 min (NEOWISE) or 90 min (ZTF), and have made time-dependent color-magnitude diagrams (CMDs; see Fig. 3), but not yet explored the Stetson index. These are some of the next steps.

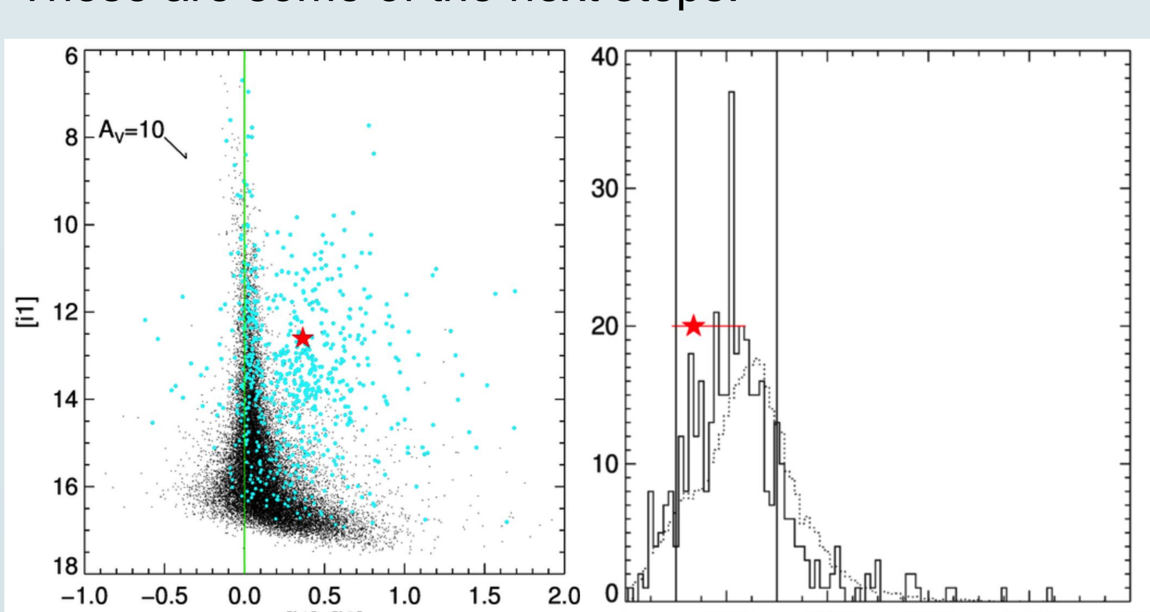


Figure 1. *Example of two plots used in to assess the YSOc in the companion poster. Left: IRAC CMD. Black dots are all stars in the catalog, cyan dots are the ~700 YSOc. Red star is one individual YSOc, this one with an IR excess. Right: histogram of Gaia distances (Bailer-Jones et al. 2018) for the entire catalog (scaled; dotted line) and the YSOc (solid line). Vertical lines at 1 & 3 kpc denote range of distances for likely members. The red star is one YSOc, with red line indicating distance uncertainties.*

Figure 2. *Press release image from Spitzer (2016, NASA/JPL-Caltech) using 1.3 μm (2MASS, blue), 3.6 μm (IRAC, green), and 4.5 μm (IRAC, red). Even in this view, many of the stars in the NS look red, which is a driving reason why we chose to explore YSO candidates based on position in the NS (see our companion poster). The research described here covers time series variability over a larger region; see Fig. 4.*

Light Curves

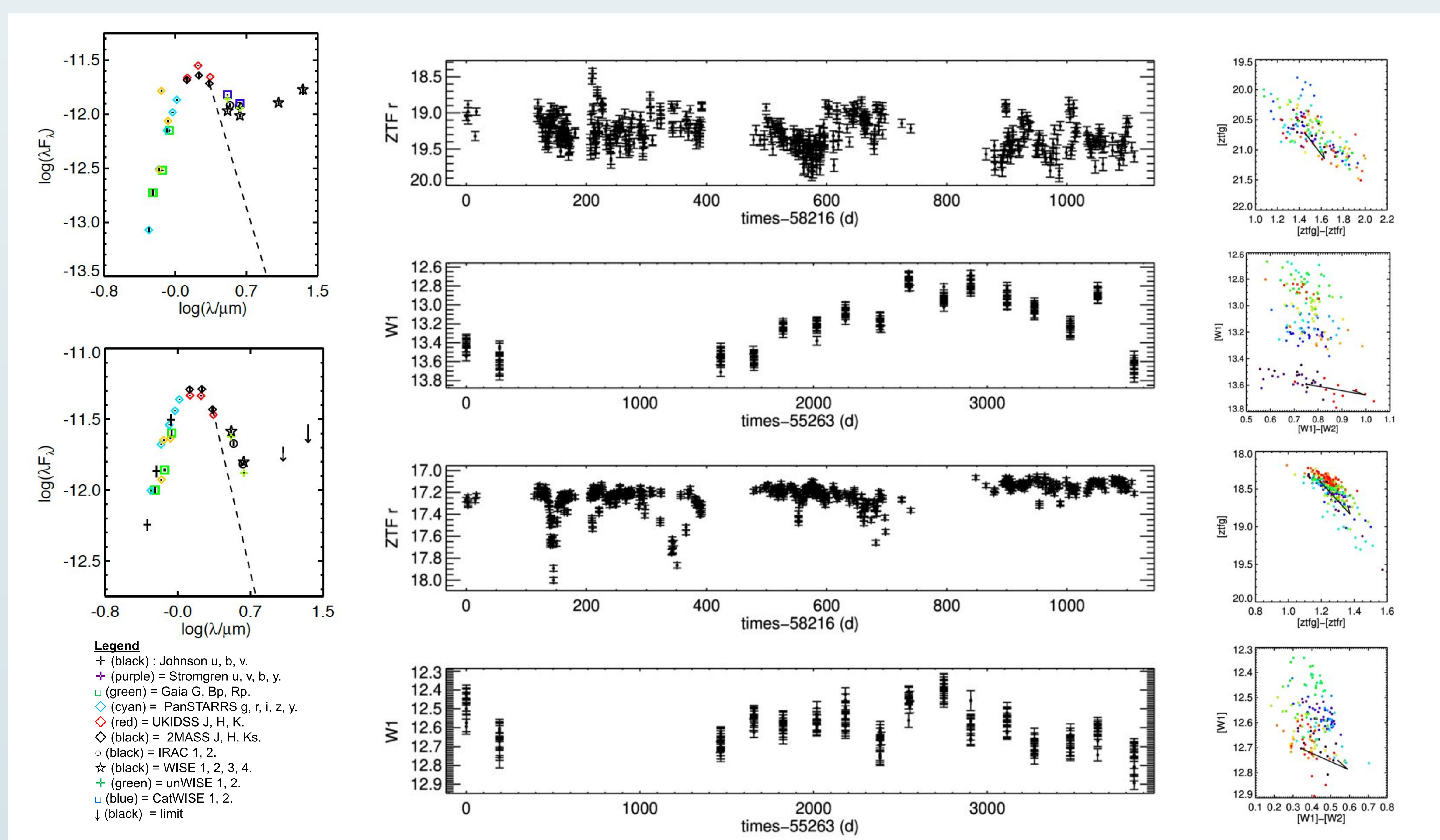


Figure 3. *Left: SEDs of two YSOc sources; symbols defined in the lower left. Dashed line is a Rayleigh-Jeans line extended from K_s to guide the eye as to where the photosphere is expected to be, assuming that K_s is unaffected by IR excess. Center: Time series LCs across available epochs in ZTF r and NEOWISE W1; these two YSOc are variable in both the optical and IR. Right: Time-dependent CMDs of two YSOc sources of interest in ZTF (r and g) and NEOWISE (W1 and W2). The colors of the points correspond to where in the LC they fall (black/purple=early, to orange/red=late). Black arrow is a reddening vector (A_v=5 mag) drawn from the first point in the series. Variations that move along that slope are likely to be due to dust occulting the central star.*

Results

For the 420 high-quality YSOc for which we have LCs from any band, the numbers that are variable in various bands appear in Fig. 4. Just 49 are variable in all four bands. About 53% are variable in the optical, and ~59% are variable in the IR.

Given the time-dependent CMDs, most seem to have variability driven by extinction variations, which is unsurprising given that they are YSOc (though it is encouraging that they have variations consistent with YSOs!).

Several of the targets are long-timescale variables and especially given their time-dependent CMDs, they are likely giants; there is at least one eclipsing binary.

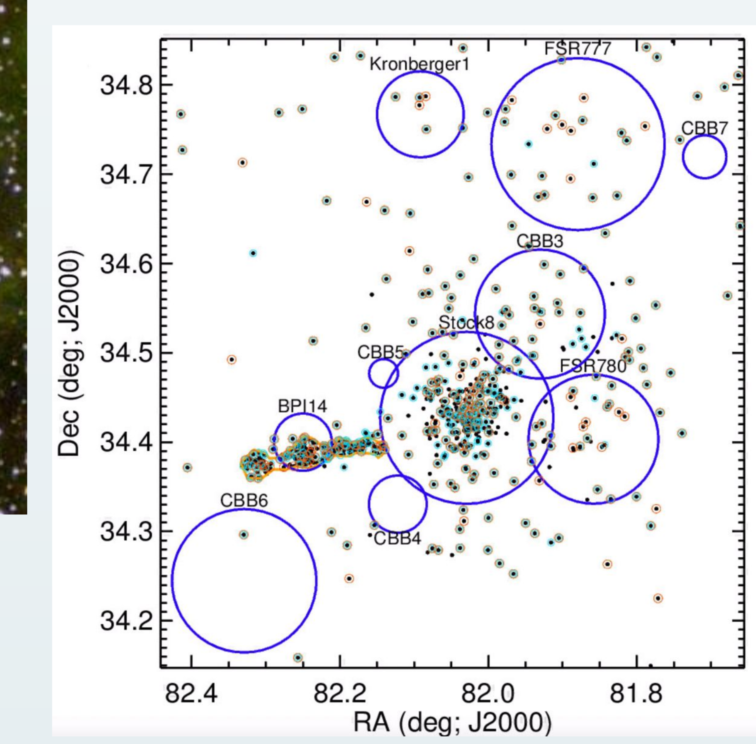
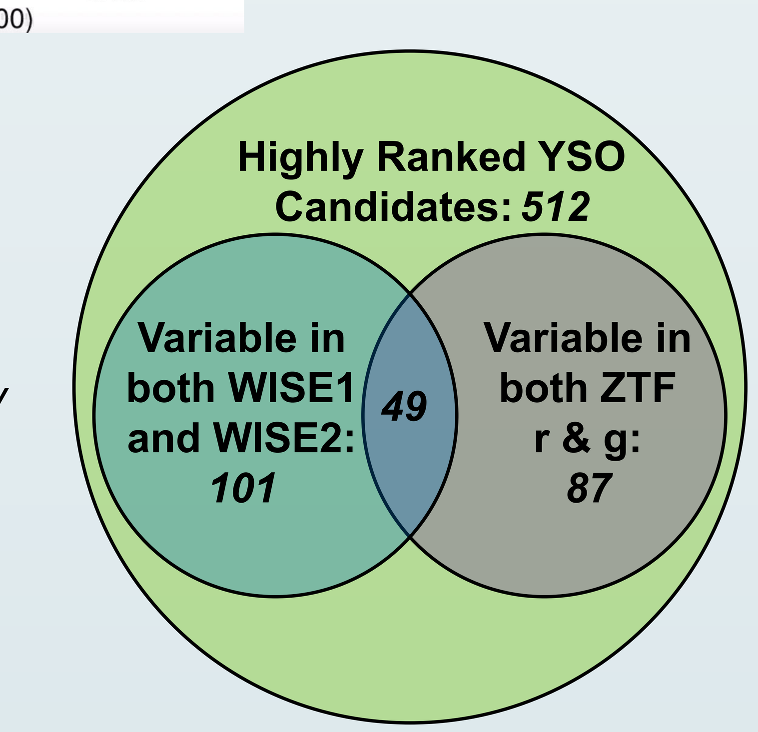


Figure 4. *Distribution of YSOc on the sky (black points) illustrating LC data in IC417 (large blue circles are literature-identified subclusters; orange polygon is our definition of the NS). Additional small cyan circle: ZTF LC exists; additional small orange circle: NEOWISE LC exists. 272 YSOc have NEOWISE LCs, 367 have ZTF LCs, and 176 YSOs have LCs in all four bands.*

Figure 5. *Venn diagram illustrating number of YSOc satisfying variability determination by wavelength.*



Future Work

- Continue evaluation for variability and periodicity using Stetson and Lomb-Scargle.
- Extend analysis to further surveys, e.g., ASAS-SN.
- Explore field stars here using χ^2 and other statistical metrics to further build catalog of variable stars in the region.
- Pursue further analysis of sources of interest, such as eclipsing binaries.

Acknowledgements

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