

SUN AND STARS: MUTUAL SYMBIOSIS

Andrea K. Dupree

Center for Astrophysics/Harvard & Smithsonian,
60 Garden Street, Cambridge MA 02138-1516, USA.
E-mail: dupree@cfa.harvard.edu

Abstract: In the 50 years since the first Solar Physics Division meeting, I have been impressed by the rewarding interactions between concepts, techniques, and results in solar physics and stellar physics. After some historical comments, several examples of this mutual symbiosis are discussed: mass accretion; plasma diagnostic techniques; unique spectroscopic probes.

Keywords: Sun, stars, orbiting solar observatories, Cambridge Cool Stars Workshops, Betelgeuse

1 INTRODUCTION

More than 50 years ago, in 1965, my thesis advisor, Leo Goldberg, Director of the Harvard College Observatory, and Henry Smith at NASA Headquarters believed that solar physics was underappreciated by the AAS and they wanted to hold separate solar meetings. John Firor (HAO Director) did in fact organize two such meetings: Boulder, CO in 1966 and Tucson, AZ in 1968. These were announced as a Special Meeting on Solar Astronomy of the American Astronomical Society. Concurrently, planetary scientists and high energy astrophysicists planned separate organizations. These threats of secession forced the AAS Council to approve AAS Divisions in 1968 with the formation of the Division of Planetary Sciences. The Solar Physics Division, along with the Division on Dynamical Astronomy and the High Energy Physics Division were formed in 1969. I was nominated as an original member of the Solar Physics Division—one of only four women among the 61 invitees. The other women were: Harriet Malitson, Helen Dodson Prince, and Elske van Panhuys Smith. At the first SPD meeting in 1970, I led a paper with Dick Munro, Bob Noyes, and George Withbroe discussing the use of Be-sequence ions as density diagnostics in the Sun (Dupree et al., 1971).

The image in Figure 1, made in 1968, illustrates both science (O VI from OSO-4) and the state of the art in image presentation at the time—we filled contours of detector count rates with colored pencils!

My PhD thesis addressed processes of ionization and excitation in plasmas, spectroscopic theory, modeling and analysis of the solar spectrum. At Harvard College Observatory we had spectroscopic instruments on a succession of satellites: Orbiting Solar Observatory-4 (OSO-4), Orbiting Solar Observatory-6, and SKYLAB. Soon after, the International Ultraviolet Explorer (IUE) was launched providing the ultraviolet spectra of stars similar to our solar studies. And

I moved between solar and stellar observations to explore these new opportunities and understand these atmospheres.

2 BEGINNING THE SOLAR-STELLAR CONNECTION

The years 1977–1978 represented pivotal times for solar and stellar physics. The series of Orbiting Solar Observatories first clearly revealed the outer solar atmosphere through studies of the ultraviolet spectrum. Then, both IUE and ‘Einstein’ (High Energy Astrophysics Observatory 2), launched in January and November 1978 respectively, demonstrated that cool stars exhibited amazingly different and diverse examples of magnetic activity that Copernicus (Orbiting Astronomical Observatory-3) had only sampled. Clearly, the study of cool stars was going to change.

On 31 January 1980 I organized a small one-day workshop to explore the many connections between solar and stellar phenomena that were emerging as a result of the new ‘stellar’ satellites and interpreted with results

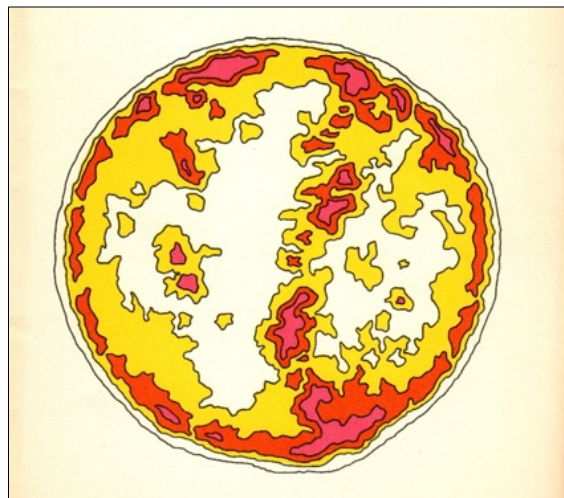


Figure 1: O VI (1032A) as imaged by OSO-4. Active regions and limb brightening are apparent (Cover image, *Wellesley Alumnae Magazine*, March 1968, reproduced with permission).

from the Orbiting Solar Observatories and SKYLAB. Members of the Solar Physics Division of the AAS were also encouraging a meeting. At that workshop, which I titled: “Cool Stars, Stellar Systems, and the Sun”, about 100 scientists participated at the Hilles Library of Radcliffe in Cambridge, MA. The Special Report 389 from the Smithsonian Astrophysical Observatory captured the reviews and contributed papers from the meeting. This was the beginning of a vigorous new field of study. We could take what we learned from the Sun—a modest cool dwarf star—and expand our understanding to stars of different masses, ages, compositions, and even to stars forming binary systems. It was a challenging and surprising time.

Concurrently, I had met a French scientist, Roger Bonnet, who was studying the ultraviolet spectrum of the Sun, and we both agreed that the time was right for a longer meeting to bring solar and stellar folks together. He was aware of NATO Advanced Study Institutes and associated funding, and suggested that we propose a meeting. Having never been to the Loire Valley, I sent him on a search for an appropriate meeting site: a castle in the Loire. We won the funding, and Roger wired me that he could not find a castle in the Loire, but “... would a chateau near Toulouse be acceptable?” And so “Solar Phenomena in Stars and Stellar Systems” came to be. The elegant chateau turned out to be the most amazing site coupled with very exciting science. The 86 participants were housed for 12 days in Bonas, France within a region known for Pousse Rapières, *foies gras*, and exploration of the Pic du Midi. Presentations, discussions, and arguments carried on for days and nights. Eugene Parker gave us an extensive, detailed, and thoughtful Summary Commentary in which he noted that “We are participating in a sudden forward surge of an important part of astronomy and physics.” He suggested that we anticipate another time to “... get together again to share our progress ...” Moreover, he concluded that “... this has been about the most rewarding meeting I have ever had the pleasure of attending.”

These two successful workshops provided additional impetus to continue. Two more meetings followed in Cambridge in 1981 and 1983. By this time, a series was born! The first workshop renamed, “Cool Stars 1”, and Bonas, dubbed “Cool Stars 1.5 ...” and the Series followed. After “Cool Stars 3”, the meeting began to travel throughout the United States: Santa Fe, Boulder, Seattle, Tucson, Athens (GA) ... and then we decided to alternate continents. In 1995, “Cool Stars 9” was held in

Florence, Italy, where the first exoplanet, 51 Peg was announced by Michel Mayor and Didier Queloz. And the meeting and 280 participants also buzzed with new discoveries of brown dwarf stars and results from Yohkoh with studies of solar X-ray emission. In addition to the United States, meetings were held in Spain (Tenerife and Barcelona), Germany, Scotland, Sweden, and France now scheduled for 2022.

In fact, the Cool Stars Workshops are the longest-running independent astronomy meetings and regularly attract over 400 astronomers for a week of lectures and discussions. A highlight consists of the splinter sessions that attendees propose and structure themselves. These meetings are scientifically rewarding with current overviews, and then opportunity for discussion on more narrowly focused topics. We had a ‘Virtually Cool’ meeting—“Cool Stars 20.5”—in March 2021 because of the pandemic. These meetings have built a vibrant community of solar-stellar researchers and strengthened interactions between the subdisciplines of solar and stellar physics.

Now I would like to offer several examples of the benefits and insights from the mutual symbiosis between the Sun and stars, as evidenced through their spectra.

3 YOUNG STARS

Young stars accrete material from their surrounding circumstellar disks that are threaded by the stellar magnetic field. The magnetic field channels disk material to the surface of the star where it forms a shock and a hot area on the stellar photosphere.

This process can be followed spectroscopically in the nearest accreting T Tauri star (Dupree et al., 2012). TW Hya is oriented with its disk facing us, so that the poles where accretion occurs are plainly visible. We identify the production of X-rays from the accretion shock using spectra from the CHANDRA X-ray Observatory. The burst of X-rays from TW Hya is followed, 9 minutes later by effects on the H- α , H- β , Helium D3 line (Figure 2), and the photospheric continuum which heats up. And 2.5 hours later, the coronal emission increases! A similar sequence of events happens also in the Sun. The AIA/Solar Dynamics Observatory observed fragments of material from a flare that fell into the chromosphere and produced hot emitting plasma (Reale et al., 2013). The arrow in Figure 3 points to the chromospheric emission produced by the falling material. The video in Reale et al. (2013) illustrates this well.

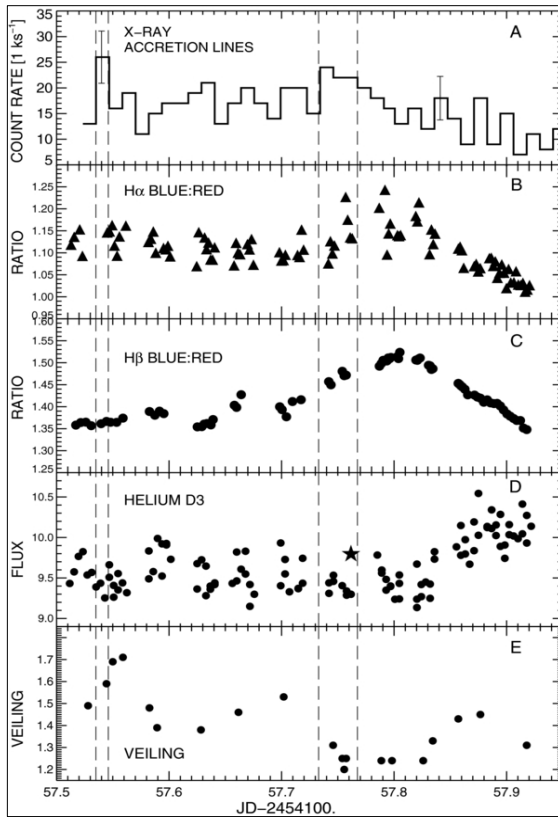


Figure 2: Sequence of spectroscopic events following the accretion of material on the young T Tauri star (after Dupree et al., 2012, page 11).

4 THE HELIUM 10830 Å LINE

Studies of the solar spectrum examined the strong relationship between the near-infrared line of He I at 10830 Å and the EUV and X-ray flux from the corona (Figure 4). Helium is photoionized and recombines, cascading to the

metastable lower level of this near infrared transition. In the Sun, active regions display greatly enhanced absorption in the helium lines. In the quiet sun and coronal hole regions, the line is substantially weaker. Similar behavior has been found in other dwarf stars (Sanz-Forcada and Dupree, 2008; Zarro and Zirin; 1986). Luminous stars offer an additional opportunity to use this transition as a diagnostic of outflows and winds (Dupree et al., 2009). Because of the metastable nature of the lower level, the profile can trace the acceleration and terminal velocity of the chromospheric plasma. Night-to-night variability occurs as well as speeds comparable to the escape velocity, 50–100 km/s (Figure 5). By contrast, outflows in solar coronal holes as detected in the helium profile are slow, amounting to about 7 km/s (Dupree et al., 1996).

The helium line has recently become a significant diagnostic in the study of exoplanets (Spake et al., 2018). Monitoring the spectrum from a star as its exoplanet transits the star has revealed a change in the line profile signaling not only the presence of an atmosphere on the exoplanet, but also frequently a comet-like tail.

Figures 6 and 7 display the excess absorption in the He I 10830 Å line during the transit of the exoplanet WASP-107b. Such observations also motivate an understanding of the behavior of the helium feature in stars other than the Sun. The Doppler shift of the line in WASP-107b corresponds to an outflow from the planet's surface of -2.35 km/s. This shift suggests that the atmosphere of the exoplanet is escaping from its extended atmosphere.

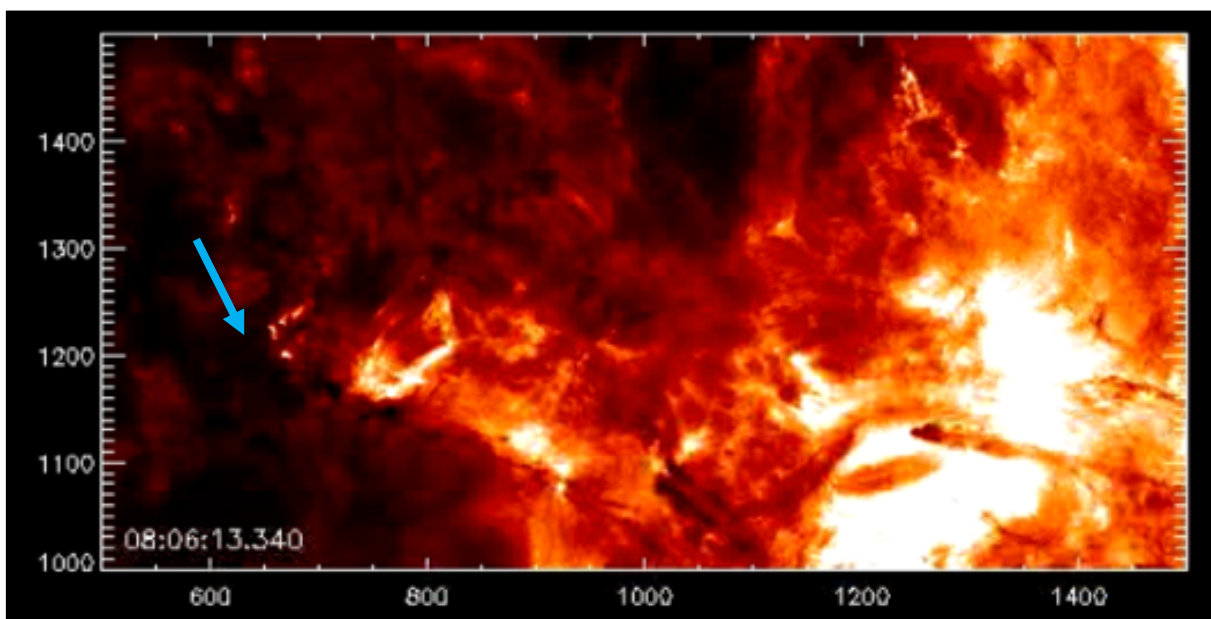


Figure 3: Chromospheric emission caused by falling flare fragments (after Reale et al., 2013: video supplement. Reprinted with permission from AAAS).

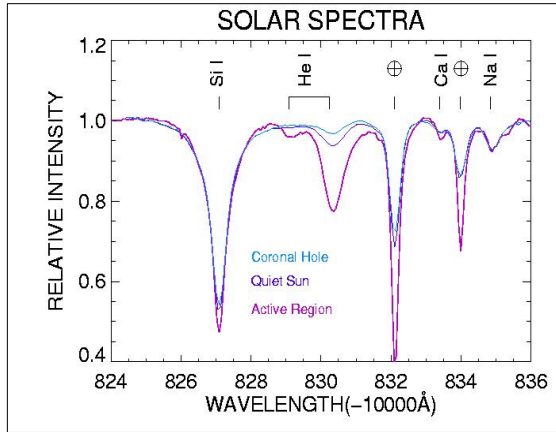


Figure 4: The He I 10830 Å line in various solar features. The association of strong absorption where nearby X-ray/EUV flux occurs is obvious from the active region spectrum (after [Sanz-Forcada and Dupree, 2008: 715](#)).

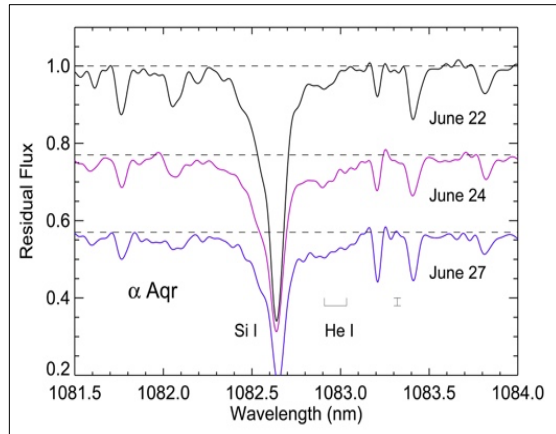


Figure 5: Night to Night variability of the He I line both in strength and terminal wind velocity in a yellow supergiant star, Alpha Aqr (plot: Andrea Dupree).

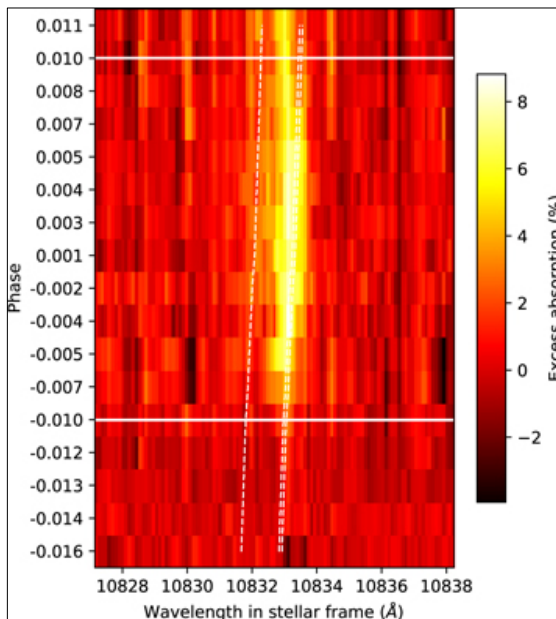


Figure 6: Excess absorption in He I 10830 Å in the stellar rest frame as a function of orbital phase of the exoplanet WASP-107b ([Kirk et al., 2020: page 4](#)).

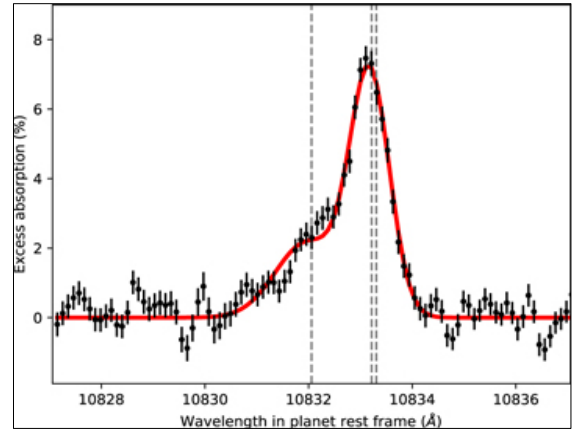


Figure 7: Excess absorption in the planet's rest frame during the transit of the host star (after [Kirk et al., 2020: page 4](#)).

5 SOLAR DIAGNOSTICS

Another intersection of solar and stellar studies occurred in the recent Great Dimming of the red supergiant, Betelgeuse, located in the shoulder of Orion. During 2019, prior to the historic dimming in early February 2020, Hubble Space Telescope acquired a series of spatially resolved near-ultraviolet spectra ([Dupree et al., 2020a](#)). The Mg II emission lines from the southern part of the star increased in flux during the fall of 2019 ([Figure 8](#)).

The change in relative strengths of the Mg II K-line between its short (V) and long-wavelength (R) components during this event were similar to the behavior of this line in the Sun when a pulse or shock travels through the atmosphere ([Gouttebroze and Leibacher, 1980](#)). As the pulse moves out from the star, the V side of the line strengthens, and then becomes weaker than the R component of the Mg II K-line as shown in [Figure 9](#). The final state in which $V < R$ is typical of outflowing material in a differentially expanding atmosphere. [Figure 10](#) exhibits a similar change in the Mg II

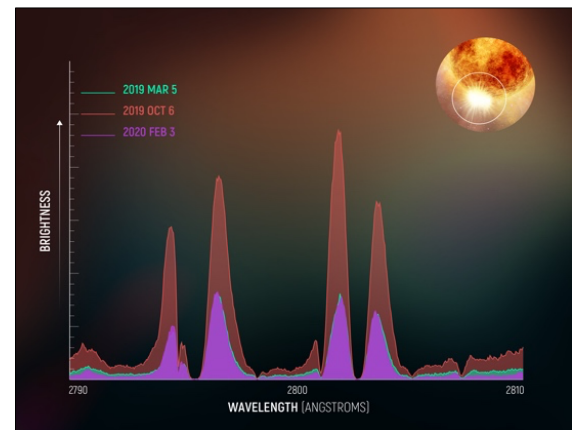


Figure 8: The Mg II lines from the south were substantially enhanced in the Oct 2019 spectrum (courtesy: NASA/ESA/J. Wheatley [STScI]).

K-line from Betelgeuse.

We can also use the electron density diagnostic of C II ($\lambda 2325.4/\lambda 2328.1$) to determine that the plasma undergoing the Mg II enhancement is denser than the surrounding plasma. Line ratios such as this were frequently used in the early studies of the solar spectrum from space, and reported in my paper at the first SPD meeting (Dupree et al., 1971).

We believe the dense material observed in Betelgeuse moved out through the atmosphere, away from the star, cooled, and condensed to form a dust cloud. The dust cloud obscured the star beginning in late December causing the historic minimum in early February and that dissipated by April 2020.

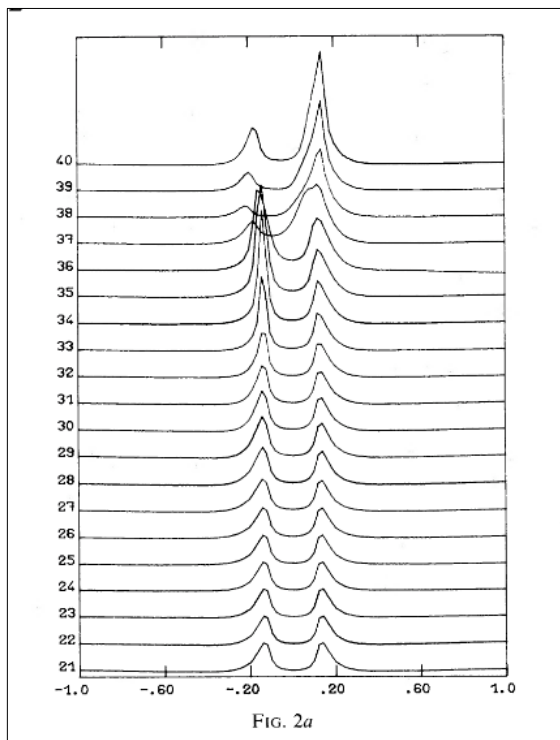


Figure 9: Calculations of the Mg II K-line profile as a pulse passes through the solar atmosphere (after Gouttebroze and Leibacher, 1980: 1142).

Studies of the Sun, observations, and modeling of important diagnostic transitions such as Mg II clearly informed the interpretation of the stellar spectra.

6 THE SOLAR SATELLITE STEREO OBSERVES A STAR

A solar satellite has been used to observe stars. Unlike the Sun, most stars are not accessible all year. For several months each year, Betelgeuse appears too close to the Sun to be observed from the Earth. During the critical period—late spring and summer of 2020—as the supergiant was recovering from its historic dimming event, it moved close to the Sun. How-

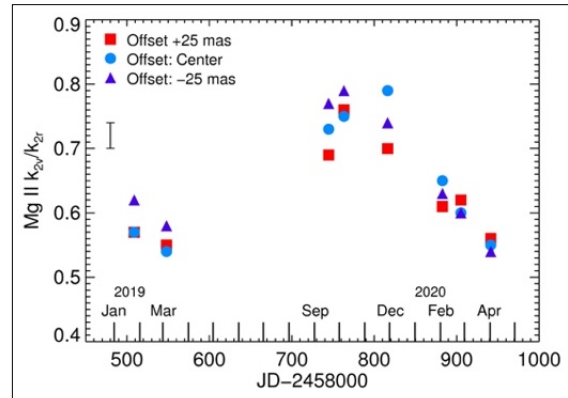


Figure 10: The ratio of the V to R peak of the Mg II K-line displaying the increase during fall 2019 (Dupree et al., 2020a: page 5).

ever, the Solar Terrestrial Relations Observatory (STEREO) is located in Earth's orbit and currently trailing at a distance corresponding to ~ 2.5 months behind the Earth's position (Figure 11). So even though, Betelgeuse could not be observed from Earth, STEREO could view the star (Figure 12)!

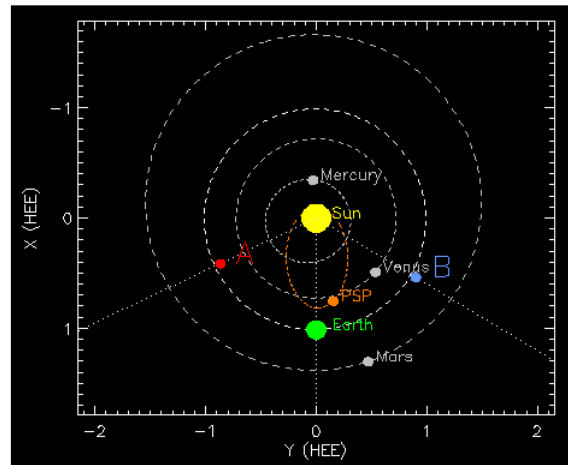


Figure 11: The position of the STEREO-A spacecraft (the red circle) currently trails the Earth in its orbit (courtesy: NASA).

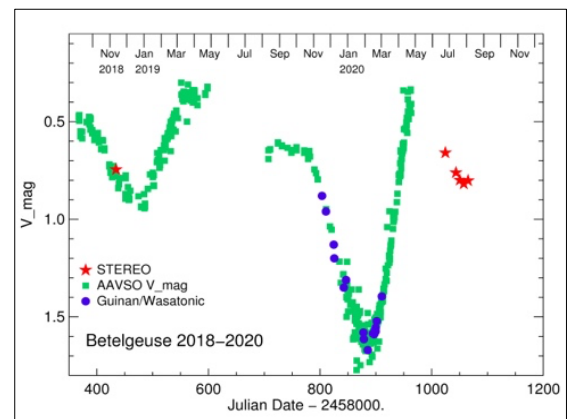


Figure 12: Measurements of the V-magnitude of Betelgeuse with the STEREO measurements marked (Dupree et al. 2020b).

The STEREO Mission Operations Team and the SECCHI Operations Team devised a role, losing ground contact, and with their wide-angle CCD were able to image Betelgeuse several times during the Summer of 2020 (see [Dupree et al., 2020b](#)).

These critical measurements revealed that the star was becoming unexpectedly fainter during the summer of 2020. With the next 'minimum' predicted to occur in April 2021, astronomers are now intensely watching this supergiant.

7 CONCLUDING REMARKS

With the advent of DKIST bringing new capabilities to ground-based solar observations, satellites probing ever closer to the Sun itself, increasing sophistication of simulations, and a broadened focus on the heliospheric environment (which impacts exoplanets too), it is an exciting optimistic time for solar physics.

I am sure that strong synergies with stellar physics will continue to exist and new ones will emerge from these increasing capabilities.

8 REFERENCES

- Dupree, A.K., Munro, R.H., Noyes R.W., and Withbroe, G.L., 1971. EUV emission lines: density sensitive multiplet ratios. *Bulletin of the American Astronomical Society*, 3, 260.
- Dupree, A.K., Penn, M.J., and Jones, H P., 1996. He I 10830 Å wing asymmetry in polar coronal holes: evidence for radial outflows. *Astrophysical Journal*, 467, L121–L124.
- Dupree, A.K, Smith, G.H., and Strader, J., 2009. Fast wind and mass loss from metal-poor field giants. *Astronomical Journal*, 138, 1485–1501.
- Dupree, A.K., Brickhouse, N.S., Cranmer, S.R., Luna, G.J.M., Schneider, E.E., Bessell, M.S., and 5 more authors 2012. TW Hya: spectral variability, X-rays, and accretion diagnostics. *Astrophysical Journal*, 750, id.73 (19pp.).
- Dupree, A.K., Strassmeier, K.G., Matthews, L.D., Uitenbroek, H., Calderwood, T., Granzer, T., and 6 more authors, 2020a. Spatially resolved ultraviolet spectroscopy of the great dimming of Betelgeuse. *Astrophysical Journal*, 899(1), id.68 (7pp.).
- Dupree, A K., Guinan, E., Thompson, W.T., and STEREO/SECCHI/Hi Consortium, 2020b. Photometry of Betelgeuse with the STEREO Mission while in the glare of the Sun from Earth. ATel#13901.
- Gouttebroze, P., and Leibacher, J.W., 1980. Solar atmospheric dynamics. I. Formation of optically thick chromospheric lines. *Astrophysical Journal*, 238, 1134–1151.
- Kirk, J., Alam, M.K., Lopez-Morales, M., and Zeng, L., 2020. Confirmation of WASP-107b's extended helium atmosphere from Keck II/NIRSPEC. *Astronomical Journal*, 159, id.115 (9pp).
- Reale, F., Orlando, S., Testa, P., Peres, G., Landi, E., and Schrijver, C.J., 2013. Bright hot impacts by erupted fragments falling back on the Sun: a template for stellar accretion. *Science*, 341, 251–253.
- Sanz-Forcada, J., and Dupree, A.K., 2008. Active cool stars and He I 10830 Å: the coronal connection. *Astronomy & Astrophysics*, 488, 715–721.
- Spake, J.J., Sing, D.K., Evans, T.M., Oklopčić, A., Bourrier, V., Kreidberg, L., and 17 more authors, 2018. Helium in the eroding atmosphere of an exoplanet. *Nature*, 557, 68–70.
- Wellesley Alumnae Magazine*, March 1968. Wellesley (MA), Wellesley College.
- Zarro, D.M., and Zirin, H., 1986. The dependence of He I λ 10830 absorption strength upon X-ray emission in late-type stars. *Astrophysical Journal*, 304, 365–370.



Andrea Dupree graduated from Wellesley College and received her Ph.D. from Harvard University. Leaving the Harvard College Observatory, she joined the Smithsonian Astrophysical Observatory in 1979 which later formed the Center for Astrophysics/Harvard & Smithsonian.

Her research focuses on spectroscopy of stars and the interstellar medium, and has ranged across the electromagnetic spectrum from radio frequencies, infrared, optical, ultraviolet and X-ray regions. She participated in science teams for IUE, EUVE, FUSE, and Kepler. She obtained the first direct image of a star other than the Sun, Betelgeuse, with the Hubble Space Telescope and recently (2020) documented the historic Great Dimming of the supergiant with spatially resolved ultraviolet spectra discovering a gigantic chromospheric outflow event. She is known for studies of young accreting stars, radio frequency recombination lines, atmospheres of luminous stars in clusters, involving processes of accretion, mass loss, and stellar winds.

Andrea is a past President and Vice-President of the American Astronomical Society. She has served on and led many committees of the US National Academy of Sciences, NASA, AAAS, the Association of Universities for Research in Astronomy (AURA), and others to determine the future course of astronomical research in the United States and other countries. She held the position of Associate Director of the Center for Astrophysics/Harvard & Smithsonian—the first woman and youngest person in that position and served as Head of the Solar, Stellar, and Planetary Physics Division at the Center for Astrophysics for a decade. Andrea founded the longest running independent astronomical meeting, Cool Stars, Stellar Systems and the Sun, which began 40 years ago. Recently, she re-assumed the position of Director of the Solar, Stellar and Planetary Sciences Division at the Center for Astrophysics, in Cambridge, MA USA.