PROCEEDINGS OF SCIENCE

Intensity Interferometry prospects with the CTAO

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A resolved optical image of a gamma-ray emitter would be of enormous scientific interest. For gamma-ray sources associated with interacting stars (colliding winds or novae), stellar intensity interferometry (SII), envisioned as a second observing mode at the Cherenkov Telescope Array Observatory (CTAO), could yield images of the systems in visible light. Recent radius measurements of massive stars with the current generation of Cherenkov telescopes demonstrate that SII is practical, but a timely and intensive effort is needed before images of interacting stars are possible. Fortunately there is also much interesting stellar astrophysics to do along the way: simultaneous mass and radius measurements, resolving stellar oscillations, and imaging outflows from stars. This contribution presents a matrix of the challenges and scientific opportunities for SII at the CTAO.

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1. Introduction

The concept of intensity interferometry as a second observing mode of a Cherenkov telescope actually goes back to a paper entitled *The effects of Čerenkov light pulses on a stellar intensity interferometer*[1], when in 1968/69 the historical Narrabri Stellar Intensity Interferometer (NSII) — in the middle of resolving massive stars[2] — placed early upper limits on gamma-ray emission from the Crab pulsar. Decades later, a paper with the converse title *Using Atmospheric Cherenkov Telescope arrays as Intensity Interferometers*[3] advocated reviving the then inactive area of intensity interferometry through the new generation of Cherenkov telescopes. In both cases, going beyond concepts and upper limits to measurements took a long time, but by now three precursor arrays of the CTAO (VERITAS, MAGIC, and H.E.S.S.) are publishing scientific results using intensity interferometry [4–6].

In the case of the CTAO, nanosecond photometry, large collecting areas, and km-scale spread, all needed for γ-ray astronomy, are serendipitously also ideal for angular resolution of stars, that is, stellar intensity interferometry[7, 8] (or SII). The main limitation comes from mirror roughness: the point spread function cannot be made smaller than the milliradian scale (compared to micro-radians for standard optical telescopes) and the resulting night sky background will drown out the interferometric signal when it becomes brighter than the target star[9]. This so-called night sky wall is expected somewhere between 8 and 10 optical magnitudes.[1]

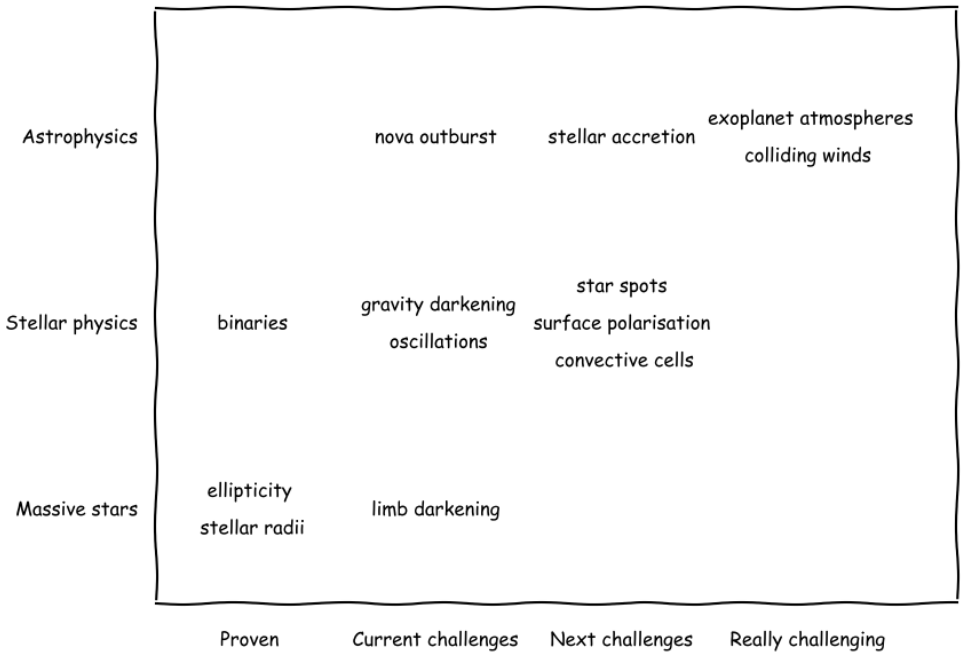

Figure 1: Science cases for stellar intensity interferometry with the CTAO, arranged according to technical difficulty versus breadth of potential impact.

[1] Though beyond the scope of this presentation, we remark that intensity interferometry is also being done using pairs of standard optical telescopes[10] and with multi-channel systems now being developed could potentially go even fainter.

Many science cases for intensity interferometry with the CTAO have been discussed[8]. Some of these were already begun by the NSII in the 1960s, some are similar to those recently worked on by Michelson stellar interferometers[11, 12] but with prospects for finer angular resolutions, while some are futuristic. In this presentation we will develop a perspective on the science cases, according to technical difficulty and scientific interest. Figure 1 is an xkcd-inspired summary. The vertical axis indicates widening scientific interest: from specialized to *massive stars*, to *stellar physics* in general, to broadly *astrophysics* including high-energy phenomena. The horizontal axis indicates technical difficulty: some are already *proven* on CTAO precursors, *current challenges* are being actively pursued, for the *next challenges* the theoretical ideas are in place but the next phase of instrumentation will be required, while the *really challenging* cases are for the later decades of the CTAO.

2. Stellar radii and binaries

Let us first consider the *proven* science cases.

Stellar angular sizes are too small for standard optical telescopes. The Michelson stellar interferometer was invented a century ago to measure them, but could only manage one star[13] (Betelgeuse). Half a century later intensity interferometry (using what is now called second-order coherence or the Hanbury Brown & Twiss effect in quantum optics) on the NSII increased the number to 32 stars[2]. Subsequent developments of Michelson interferometry have gone further, but stellar intensity interferometry (SII) with the CTAO would have many thousands of potential targets. Figure 2 indicates the stars available even with an initial deployment of SII on the CTAO.

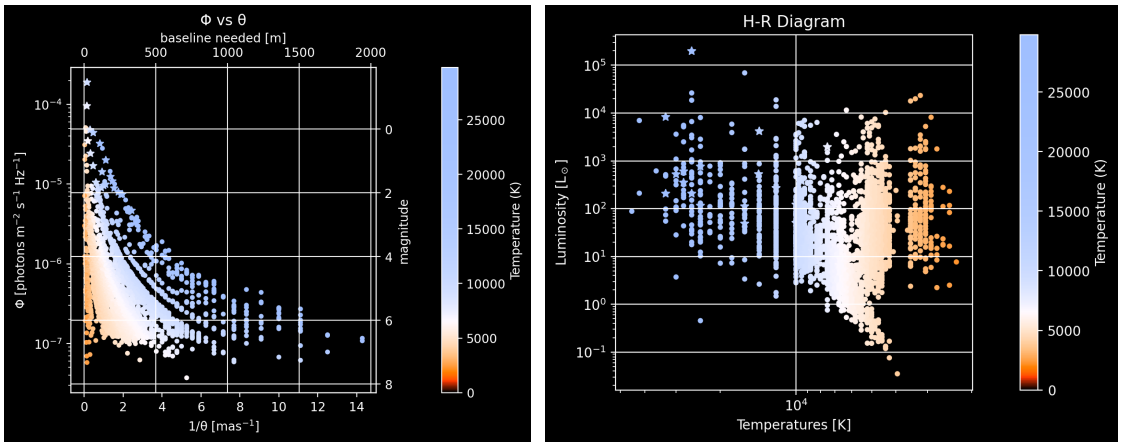

Figure 2: Bright stars (upto $m_V \simeq 7$) that would be candidates for intensity interferometry. The right panel shows an H-R diagram. The left panel shows the spectral photon flux Φ against the inverse angular diameter. Star symbols indicate the stars observed by the NSII. For an interactive version of this figure see

https://target-stars-sii.streamlit.app/

Binaries are more challenging than single stars, but also contain additional scientific interest. The interferometric signal changes as the orbit evolves, and meanwhile the telescope locations on the

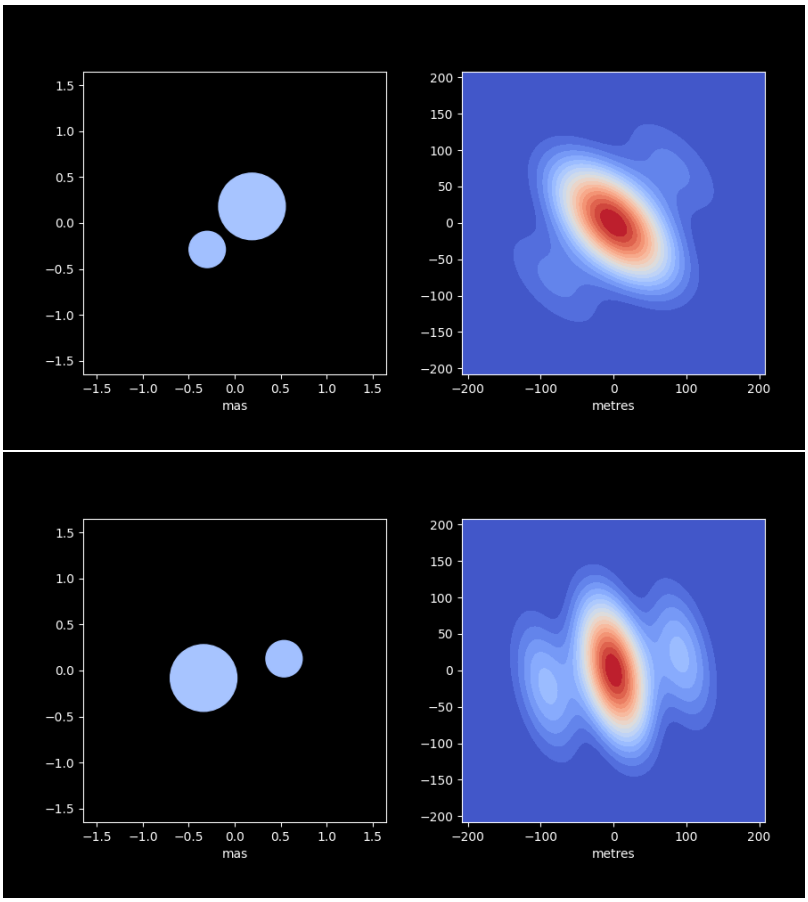

Figure 3: Illustration of Spica and its expected interferometric signal at opposite orbital phases.

interferometric plane also change as the Earth rotates. Figure 3 illustrates the signal for Spica, giving some feeling for the difficulties involved. Nevertheless the NSII resolved the orbit of Spica[14] and measured the radius of the larger star. Simulations indicate that the radius of the smaller star could also be measured [15]. The advantage of an orbital solution, obtained by combining interferometric and spectroscopic observables is that masses and distances can be inferred as well. The most famous example of such an orbital solution (and also the most famous example of Michelson stellar interferometry) is the relativistic orbit of S2 around the the Galactic-center black hole[16]. The Galactic center is not a target for SII with the CTAO, as it can be observed only in the infrared, but there are many close binaries accessible to the CTAO in SII mode.

3. Features of theoretically known shape

While radius and orbit measurements are interesting, the SII resolution possible with the CTAO motivates going further and resolving features on the surface of stars. In this section we consider features that can be described theoretically by a global model with a few parameters that could be fitted.

The simplest feature that goes beyond representing a star as a uniform disk is limb darkening. The physical reason is that light from different parts of a star goes through different lengths of the

stellar atmosphere. Thus the rim of the Sun appears redder and darker than the middle, and the same is expected from other stars. The NSII did consider the effect[17] but did not have the SNR for interesting observational constraints. Limb darkening will likely be the next item to move into the *proven* column.

Ellipticity or rotational flattening in rapidly-rotating stars was not considered at the time of the NSII, though it may actually have been already measurable. VERITAS has recently moved such measurements to the *proven* category[18].

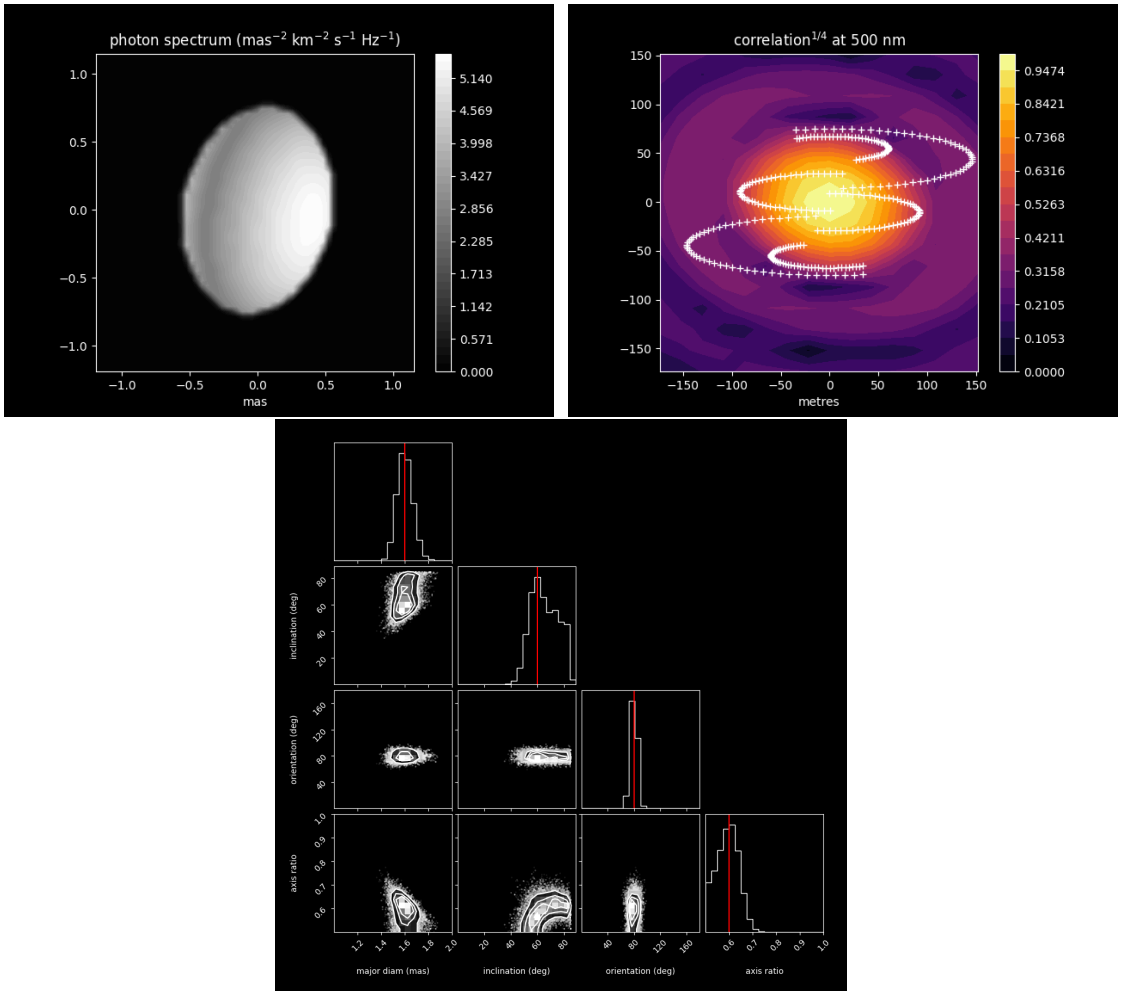

Figure 4: The upper left panel shows a model stellar profile in a model roughly approximating Regulus with gravity darkening. The upper right panel panel shows the interferometric signal with Earth-rotation tracks corresponding to three telescopes. The lower panel shows parameter recovery from simulated data.

Fast rotators are expected to exhibit a further novel phenomenon: gravity darkening. On a star that is ellipsoidal because of rotation (or alternatively because of tidal effects), surface gravity is less at the radially larger regions, and the effective temperature is less. Gravity darkening has been extensively studied using theoretical models[19] and has been resolved using Michelson interferometry by CHARA[20]. Figure 4 simulates how gravity darkening and its SII signal might appear. The simulated star exhibits not only flattening but also a gravity-darkened equatorial region,

indicating the inclination of the spin axis. The figure also shows the intrinsic axis ratio and the spin orientation recovered from the simulation. Assuming the model is correct, even a three-telescope array would suffice.

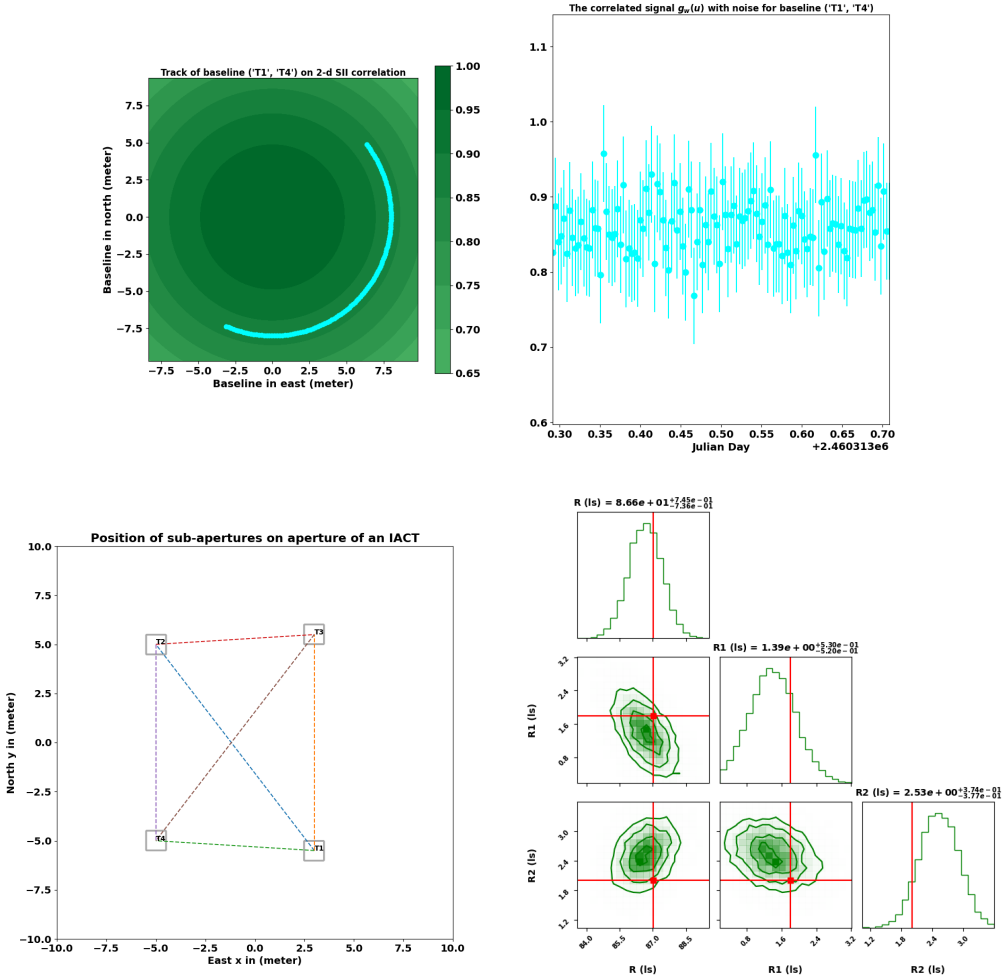

Figure 5: Simulations (from Rai et al, in prep) of angular-diameter measurements of Polaris. The lower left panel considers four segments of a single mirror. The upper left panel shows the interferometric signal and track due to the two lowest mirror segments. The upper right panel shows a simulated signal. The lower right panel shows a fit to a three-parameter fit $R + R_1 \cos(2\pi t/P) + R_2 \sin(2\pi t/P)$. The amplitude of pulsation is unrealistically large (a few percent rather than 0.5%).

Resolving stellar pulsations is an attractive prospect, as it needs an accurate diameter measurement but varying in time with a known period (though not an already-known phase, because brightness and radius are not in phase). A good example is Polaris, the nearest Cepheid variable, and indeed it has been targetted using Michelson interferometry on CHARA[21]. Figure 5 shows a simulation assuming four segments of a single Cherenkov telescope. The advantage in this example that the telescope does not need to track — pairs of telescope segments automatically trace different slightly elliptical arcs in the interferometric plane.

Another prospect is to measure polarization across a star. Theory predicts that the net polarization cancels across the surface of a spherical star, but not so for a fast-rotation. A net polarization has been measured for Regulus[22], and resolved polarization would be even more interesting. Hanbury Brown and collaborators did attempt with the NSII to detect a corona around Rigel using polarization but were not successful[23].

Much more challenging than these —but still having a good theoretical model with a few parameters— is the case of exoplanet transits. Figure 6 shows a simulation based on one of most favorable potential targets: HD 332231, which is a warm Saturn around a hot dwarf star[24]. If the planetary spectrum has an absorption line, measuring on and off the line could resolve the planetary atmosphere. Particularly enticing is the possibility of resolving surface winds on the planet, if the absorption line is different on one side of the planet than on the other. The planet would then appear larger on one side than the other, perhaps mushroom-shaped.

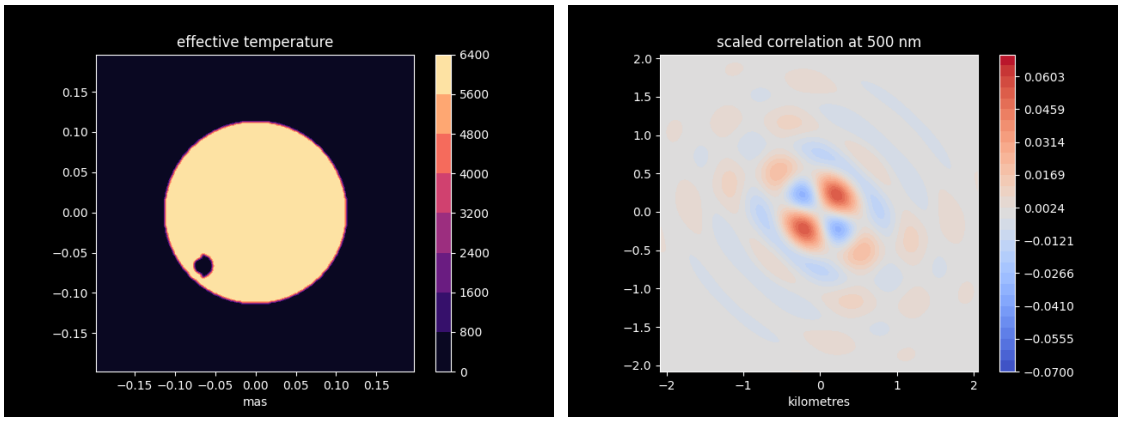

Figure 6: Simulation of a transit HD 332231 b across its host star. The mushroom shape of the planet is fanciful (see text) but the signal shown in the right panel (which is the different with respect to the off-transit signal, a roughly 1% difference) is indicative.

4. Features of unknown shape

All the cases we have considered so far have models with a few parameters, which can be fitted to data on the interferometric plane. Now we move on to situations where the basic process may be well understood, but the image will not have a simple form, and requires image reconstruction. So far there has been relatively little work on image reconstruction specifically in the context of SII[25], but algorithms developed for Michelson interferometry can be reasonably expected to carry over, as the main observable (interferometric visibility squared) is the same. We will not discuss image reconstruction further here, only the potential applications.

Starspots are more important than they may appear. Sunspots are probes of the solar dynamo, models of which are far from settled[26], and the magnetic fields in stars surely contain more mysteries to solve. Starspots are typically studied using eclipses or transits, but work on resolving them has been done with Michelson interferometry on CHARA[27].

Continuing the comparison with the solar surface, convective cells on the Sun are comparatively small and number about two million, but giant stars are predicted to have just a few giant convective

cells[28]. Michelson interferometry has resolved some examples, using VLTI[11] and CHARA[12]. The larger baselines and denser coverage of the interferometric plane that CTAO can achieve are promising in this regard.

In terms of multi-messenger sources, in the sense of being γ-ray emitters that could be resolved using SII, binaries with colliding winds are the most promising candidates. The γ^2 Velorum system, consisting of two hot stars, one of them a Wolf-Rayet, and studied already by the NSII[29] surely has some degree of colliding winds. But closer binaries may be stronger in this regard. This is an area where fluid-dynamics simulations would be especially welcome.

In contrast to colliding-wind systems, are binaries where one star (or stellar remnant) is compact, and accretes from the larger star. Among mostly steady accreting systems, the most promising candidate for SII appears to be Vela X-1. It consists of a blue supergiant and a neutron star. The system is a well-known X-ray source, as a result of the accretion. Current models include hydrodynamical simulations of the accretion process[30].

Accreting systems can also lead to spectacular target-of-opportunity events, namely nova outbursts. The most-discussed system at the moment is T Coronae Borealis. It consists of a white dwarf accreting from a red giant. Thermonuclear runaways sporadically occur at the accretion disk, making the system a recurrent nova. The last outburst was in 1946, and some indicators suggest that the next one is imminent[31]. Should the system be kind enough to erupt in the night sky, SII from even current Cherenkov telescopes may be able to resolve the expansion during the few hours.

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