Tycho's (Super)Nova

In 1572, the Danish astronomer Tycho Brahe observed a new star in the constellation of Cassiopeia (see Fig. 1). In the following year, he described his observations in the report *De Nova Et Nullius Aevi Memoria, A Mundi Exordio Prius Conspecta Stella*[1], and the term *nova* entered into the astronomical lexicon to refer to stars that show sudden and dramatic brightening episodes.

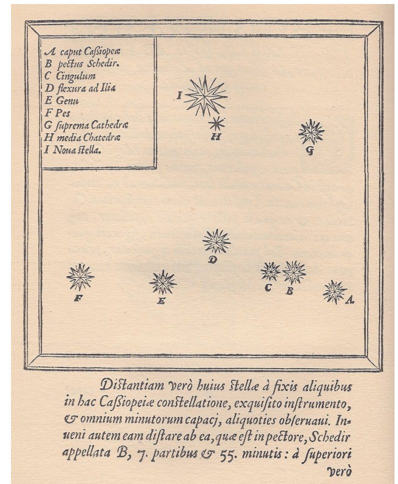

Figure 1: Sketch of the constellation Cassiopeia, drawn by Tycho Brahe to show the position of the new star (marked *I Noua stella*). From *De Nova*. . . .

[1] Loosely translated, "Concerning the Star, new and never before seen in the life or memory of anyone".

Types of Novae

Nowadays, we divide novae into four different categories:

- *classical novae*, where the star brightens over a few days to reach a peak luminosity $L \sim 10^5\,L_\odot$, and then fades away over timescales of a few months.
- *recurrent novae*, where the star passes through multiple episodes each resembling a classical nova. The timescales for recurrence extend from years through to centuries.
- *dwarf novae*, where the star passes through multiple brightenings, but with a much lower peak luminosity ($L \sim L_\odot$) than recurrent novae. The timescales for recurrence extend from days to decades.
- *supernovae*, where the star brightens over a couple of weeks to reach a peak luminosity $L \sim 10^{11}\,L_\odot$, and then fades away over timescales of many months.

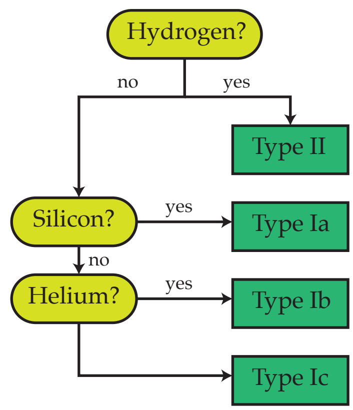

Figure 2: Flow chart for the classification of supernovae, on the basis of whether absorption lines from various elements can be seen in the spectrum. Note that some type Ic supernovae do show silicon liens, but they are much weaker than in type Ia.

Cataclysmic Variables

The nova categories, above, all arise in a special class of binary star system: *cataclysmic variables*. These consist of a white dwarf that accretes matter from a companion star that's in an earlier evolutionary phase (e.g., main sequence or RGB).

Classical and recurrent novae occur due to the steady build-up of hydrogen fuel on the surface of the white dwarf. As the hydrogen layer accumulates, it reaches sufficient temperatures[2]for the CNO cycle to begin. The hydrogen ignition takes place under degenerate conditions, and so the star experiences a hydrogen flash. During the outburst, the white dwarf exceeds the Eddington luminosity limit[3], and some of the hydrogen is driven off into space. The remaining hydrogen burns into helium, and merges with the underlying helium layer.

After the burning ceases (typically, a few months), the white dwarf resumes accretion, building up a fresh hydrogen layer. Eventually, it will undergo another nova outburst. However, the timescale be-

[2] The hydrogen layer heats up when it is compressed by the white dwarf's strong surface gravity.

[3] See *Handout* xxviii.

tween outbursts can be very long, especially if the accretion rate is slow and/or the white dwarf mass is low[4]. This explains the difference between classical and recurrent novae: they are both intrinsically the same phenomenon, but in the former the timescale between outbursts is so long that astronomers have only ever seen a single one[5].

With their much smaller peak luminosities, dwarf novae arise from a different process. Although there remain many uncertainties, the current best narrative is that their outbursts (which are much less energetic than classical or recurrent novae) arise due to a sudden increase[6]into the accretion rate onto the white dwarf, with the consequent rapid release of gravitational energy.

[4] The mass of the white dwarf determines how much hydrogen has to accrete before it ignites; more-massive white dwarfs have stronger surface gravities, and therefore can more easily heat the hydrogen to the ignition point.

[5] Of course, a classical nova will be re-categorized as a recurrent nova if and when it shows a second outburst.

[6] This increase is itself driven by changes to the viscosity of the accretion disk.

[7] Type Ib, Ic and II supernovae do not arise from cataclysmic variables, but from the core collapse of a massive star.

Thermonuclear Supernovae

The *nova stella* observed by Tycho was in fact a type Ia (thermonuclear) supernova. Supernovae are among the most energetic phenomena in the Universe. We classify them on the basis of the absorption lines seen in their spectrum (see Fig. 2).

Type Ia supernovae occur[7] in cataclysmic variables when the mass of the accreting white dwarf reaches the *Chandrasekhar mass limit* $M_{\rm ch} \approx 1.4\,{\rm M}_{\odot}$. Approaching this limit, relativistic effects in the degenerate electrons cause the stellar radius to shrink at an accelerating rate. This compression drives up the temperatures of the carbon and oxygen ions comprising most of the white dwarf's mass, and eventually they ignite in an explosive carbon-oxygen flash. The resulting energy release ($\sim 10^{51}$ erg) suffices to completely destroy the star.

Observations of the light curves of many type Ia supernovae reveal they share a similar morphology (see Fig. 3). In the 1970's, a number of astronomers noticed that the rate of dimming after maximum brightness is related to the absolute magnitude (or alternative, luminosity) at the maximum. In the 1990's, Mark Phillips placed this correlation on a quantitative footing with the empirical relation

$$M_{\rm max}(B) = -21.726 + 2.698\Delta m_{15}(B). \qquad (1)$$

Here, $M_{\rm max}(B)$ is the maximum absolute magnitude of the supernova in the B-band; and Δm_{15} is the change in the apparent magnitude in the B-band, over the 15 days after the maximum. Using this *Phillips relation*, we can determine the absolute magnitudes of supernovae from their light curves, and thereby measure their distances.

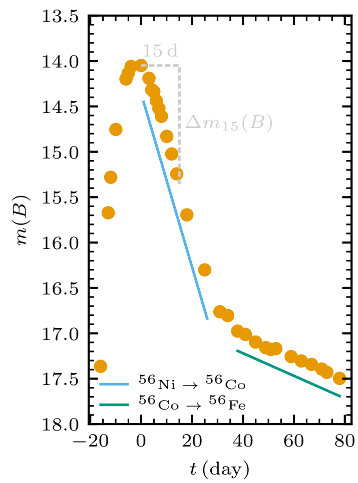

Figure 3: Light curve in the B-band (corresponding to wavelengths around 4450 Å) for the supernova 2002bo. The $t = 0$ point is defined as maximum brightness, when $m_B \approx 14.0$. The dashed lines indicate how the 15-day brightness change, $\Delta m_{15}(B)$, is measured. The solid lines indicate the primary energy source powering the supernova's luminosity; at early times ($t \lesssim 30$ d, this source is the radioactive decay of ^{56}Ni into ^{56}Co, whereas at later times it is the decay of ^{56}Co into ^{56}Fe. Data from Ganeshalingam et al. (2010, *ApJS*, **190**, 418.

Further Reading

Kippenhahn, Weigert & Weiss, §36.1; *Ostlie & Carroll*, §§15.2; *Prialnik*, §§10.5,11.6.