TEACHER NOTES – ASTRONOMY IN THE NEWS #05

DIMMING OF BETELGEUSE

Slide 2 – Background Science: Red Supergiants

The evolution of a star depends on the initial mass of the star. Stars form from molecular clouds and once they are formed, they join the main sequence. This is where the paths deviate. Stars that are smaller than 8 solar masses (8 times the mass of the Sun) become red giants, then planetary nebulae, and finally a white dwarf. However, stars that are larger than this become red supergiants, which then explode with a supernova, leaving either a neutron star (less than 40 solar masses) or black hole (larger than 40 solar masses), depending on the mass of the star at the point the star explodes.

Red supergiants have moved from the main sequence in the Hertzsprung-Russell Diagram (described below). They become redder (i.e. lower temperature) and have very high luminosities. The Stefan-Boltzmann law indicates that they have large radii:

$$L = 4\pi R^2 \sigma T^4$$

where L is stellar luminosity, R is the radius of the star, σ is the Stefan-Boltzmann constant and T is the effective temperature of the star.

Stars become red supergiants once they exhaust the hydrogen in the cores and begin to burn helium and larger elements. As red supergiants are massive enough to fuse heavy elements, they do not lose their outer most layers as planetary nebulae, unlike lower-mass stars.

The red supergiant phase lasts approximately 100,000 years and experiences significant mass loss throughout. Before a red supergiant goes supernova, the mass loss rate increases.

IMAGES:

1. (Top left) Cartoon demonstrating the different life cycles of stars depending on their initial mass. The top row is for stars less massive than 8 solar masses, whilst the bottom row is for stars with an initial mass of 8 solar masses or greater. A further differentiation is made with the most massive stars at 40 solar masses, where below that the supernova leaves a neutron star, whilst greater than that, a black hole remains.
2. (Top right) Hertzsprung-Russell (HR) Diagram is a way of plotting stars to show their evolution throughout time. The HR diagram can either be theoretical, or observational. Theoretically, it plots temperature of the star against its luminosity, whilst observationally, it plots the spectral type (which is determined from the spectrum of light from the star) against absolute magnitude (observed brightness corrected for distance). A red supergiant will have started on the main sequence, and then moves to the supergiant area, i.e. it becomes redder.

3. (Bottom) Cartoon depiction of a red supergiant star. The left-hand side shows the expansion of the outer-most stellar envelope. It demonstrates that these stars grow to a size comparable with the orbit of Jupiter. The right-hand side shows the "onion-skin layers" of burning within the core, from the outermost hydrogen fusing layer down to the iron core.

Slide 3: Dimming of Betelgeuse

Betelgeuse is usually the tenth brightest star in the night sky. However, from November 2019 to March 2020, it dimmed from its usual brightness of 0.1-1.0 magnitudes to 1.614 magnitudes. Magnitudes are a logarithmic system where a larger number indicates a dimmer system. A change in 0.614 would indicate that it is 1.76 times less bright and a 1.514 change in magnitudes would indicate it is 4.03 times less bright.

This dimming was attributed to four possible scenarios:

1) A decrease in effective temperature (maybe a small scale change)
2) Occultation from newly formed dust from Betelgeuse
3) Occultation from dust transiting in front of the star
4) Change in the angular diameter of Betelgeuse.

Scenarios 3) and 4) were ruled out due to the observations taken. A foreground clump of dust would have moved in relation to Betelgeuse, however, the dark patch in the images always remained in the southwest quadrant of the images (as can be seen in image one outlined below). The size of Betelgeuse was measured to be 42.11 milliarcseconds to 42.61 milliarcseconds. However, this size range is consistent with that of 30 years of measurements and a 30% change in radius would be required to cause the level of dimming observed.

The remaining two scenarios both required computer models to compare to observations. The parameters of these models are altered until they match the observations, with the best fitting model for each observational epoch chosen. The first model simulates a stellar photosphere and provides temperatures for Betelgeuse. The model suggested a temperature of 3,200 K and 3,400 K compared to an unperturbed temperature of 3,700 K.

The second models the physical conditions of a clump of dust in front of the star. The initial conditions of the second model were a spherical clump of dust heated from behind by a red supergiant. These models suggested a clump of dust of mass 0.7 – 3.0 $\times 10^{-7}$ solar masses. This would be 35-128% of the annual mass loss from Betelgeuse with a low-mass loss rate assumption or 3-12% if a high-mass loss rate is used.

The two scenarios are both feasible as they replicate the optical dimming observed and the structure observed. However, the dimming in the infrared is not replicated by either scenario. They can, though, replicate this if both scenarios are combined. A change in surface temperature combined with a dust cloud in our line of sight resulted in the great dimming that was observed.

As a result, there is not thought to be an imminent supernova, which would be so bright that it would be visible in the daytime. Light curves of stars about to supernova show an increased mass loss in the final weeks to centuries of their lives. The current mass loss rate is calculated to be 2.0×10^{-7} to 2.0×10^{-6} solar masses per year, with pre-supernovae stars having a mass loss rate of 10^{-4} to 1 solar masses per year.

IMAGES:

1. (Top left) Hα (a red, visible line in a spectrum at 656.28 nm) images of Betelgeuse over approximately 15 months. This shows the dimming of the star, along with it getting brighter in the last image taken in March 2020. These images were taken by the Very Large Telescope in Chile.
2. (Top right) The two models at each epoch of observations. The top line demonstrates the change in photosphere temperature, whilst the bottom line shows the changes in observed brightness with a dust clump in our line of sight. These are the parameters that best fit the observations. They can be compared to the observations in the image described above.
3. (Bottom left) Light curve showing the brightness of Betelgeuse in a visual wavelength. This shows the rises and falls of the brightness over the past 6 years. The vertical blue lines show the dates of the observations in this paper.
4. (Bottom right) Map of Betelgeuse in 7mm emission from the Very Large Array in New Mexico. This is radio emission and shows the extended nature of the structure, with the size of the optical disk displayed. The extension shows how far the photosphere is expanded in a red supergiant star, as well as any dust that is expelled from stars in this stage of their evolution.

The article that this resource is built on can be found here:

https://www.bbc.co.uk/news/science-environment-57501416

A free version of the research article can be found here (I will note that I do not know how long access will remain free):

https://www.nature.com/articles/s41586-021-03546-8.epdf?sharing_token=SIvSibg7dEmX-qewJNb2a9RgN0jAjWel9jnR3ZoTv0OnnGNKD24yn-b4ktkxhPv3jPIlYZWHPKOseJdqtKalNP7S8p6YtYoyYhrJaczD7OMY9LazDtE_HreK37uWVZgfLaZWXrEJ5MEqW4_qsNKNSSvGkYvIbvrtreQp8Yt3eMwjnuVTF_lguocZLrvVfEAAxa3qvcUTLg2zcAjngYpTYlliKZbbD93x7KfzQQlOEOg%3D&tracking_referrer=www.bbc.co.uk

Slide 4 – Activity: Periodicity of Betelgeuse

Can you calculate the periodicity of the usual dips in the brightness of Betelgeuse? This should be calculated from the dates shown on the slide, and then an average taken. The average of the three periods shown is 384 days. The 20-year average is 400 days. This would imply that the period is consistent with the 20-year average.

GCSE Specifications:

Specification	Knowledge Point
Pearson Edexcel Astronomy	6.2, 13.1, 13.2, 13.4, 13.5, 13.6, 13.7, 13.8, 13.10, 14.2, 14.6, 14.10
Pearson Edexcel Physics	7.17, 7.18
AQA Physics	4.8.1.2

A-Level Physics Specifications:

Specification	Knowledge Point
Pearson Edexcel Physics	159, 160
OCR Physics A	5.5.1 (e, g), 5.5.2 (e, j)
AQA Physics	3.9.2.1, 3.9.2.4, 3.9.2.5, 3.9.2.6