HSC Enrichment Day

Astrophysics Option

Helen Johnston
University of Sydney

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Hertzsprung-Russell diagram

Observations – what we see

Theory – understanding

Dissances – magnitudes

Masses – binaries

The central role of gravity
Here’s the most basic version of the Hertzsprung-Russell diagram.

- **hot, bright**
- **cool, bright**
- **hot, dim**
- **cool, dim**

**main sequence**
- = 90% of stars
Here’s the most basic version of the Hertzsprung-Russell diagram.

Other distinct groupings of stars can be identified.
Interlude 1
The luminosity of a star

In order to place stars on the HR diagram, we have to know how bright they are. In particular, we have to distinguish between stars which are intrinsically bright, and stars which just appear to be bright because they are close to us.
Compare a list of the *brightest* stars with a list of the *nearest* stars.

<table>
<thead>
<tr>
<th>Brightest</th>
<th>Nearest</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>star</strong></td>
<td><strong>star</strong></td>
</tr>
<tr>
<td><strong>apparent</strong></td>
<td><strong>apparent</strong></td>
</tr>
<tr>
<td><strong>magnitude</strong></td>
<td><strong>magnitude</strong></td>
</tr>
<tr>
<td><strong>d (pc)</strong></td>
<td><strong>d (pc)</strong></td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td><strong>Sirius</strong></td>
<td>Proxima Centauri</td>
</tr>
<tr>
<td>−1.50</td>
<td>11.5</td>
</tr>
<tr>
<td>2.6</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Canopus</strong></td>
<td>Alpha Centauri</td>
</tr>
<tr>
<td>−0.73</td>
<td>0.1</td>
</tr>
<tr>
<td>96</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Alpha Centauri</strong></td>
<td>Barnard’s Star</td>
</tr>
<tr>
<td>+0.10</td>
<td>9.5</td>
</tr>
<tr>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Vega</strong></td>
<td>Wolf 359</td>
</tr>
<tr>
<td>+0.04</td>
<td>13.5</td>
</tr>
<tr>
<td>7.9</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Arcturus</strong></td>
<td>Lalande 21185</td>
</tr>
<tr>
<td>0.00</td>
<td>7.5</td>
</tr>
<tr>
<td>11.6</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Capella</strong></td>
<td>Sirius</td>
</tr>
<tr>
<td>+0.05</td>
<td>−1.5</td>
</tr>
<tr>
<td>13.1</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Rigel</strong></td>
<td>Luyten 726–8</td>
</tr>
<tr>
<td>+0.08</td>
<td>12.5</td>
</tr>
<tr>
<td>184</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>Procyon</strong></td>
<td>Ross 154</td>
</tr>
<tr>
<td>+0.34</td>
<td>10.6</td>
</tr>
<tr>
<td>3.5</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Betelgeuse</strong></td>
<td>Ross 248</td>
</tr>
<tr>
<td>+0.41</td>
<td>12.2</td>
</tr>
<tr>
<td>131</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>Achernar</strong></td>
<td>Epsilon Eridani</td>
</tr>
<tr>
<td>+0.47</td>
<td>3.7</td>
</tr>
<tr>
<td>45</td>
<td>3.3</td>
</tr>
</tbody>
</table>
The inverse square law means that once we know how far away a star is, we know how bright it really is.

We define the \textit{absolute magnitude}:

\[ M = m - 5 \log \left( \frac{d}{10} \right) = m - 5 \log d + 5 \]

where \( d \) is the distance to the star in parsecs, and \( m \) is its apparent magnitude.

The \textit{absolute magnitude} of a star is the magnitude it would have if it were at a distance of 10 pc.
Let’s have another look at that Hertzsprung-Russell diagram.
The relation between luminosity and temperature tells us there is an underlying physical link between these properties.

For example, consider an alien scientist constructing a similar diagram for school children.
Our intrepid scientist measures as many numerical quantities as zyx can. Plotting the children’s weight against the last two digits of their telephone number shows no pattern.
But plotting weight against height shows a decided pattern: indicating there is an **underlying factor**.
This factor is, of course, *age*. Picking children of the same age finds this pattern. And a single child would trace out the curve as he or she grew.

So is this the explanation for the main sequence – an age sequence?
It’s different for stars. We can see this by looking at stars of the same age – in clusters.

[Graph showing the relationship between temperature (K) and L/L(Sun) for very young clusters, e.g., Pleiades.]
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![Graph showing luminosity ratio (L/L(Sun)) vs. temperature (K) for stars in an old cluster, e.g., globular cluster M10.](image-url)
So if it’s not age which is the underlying factor for stars, what is it?

It’s *mass*.  

The main sequence is a *mass* sequence, not a time sequence. All the properties of a star are dictated by its *mass*. 
Why is mass the important factor for stars?

Because the whole of a star’s life is a sequence of attempts to hold off gravity.
Gravity.
It isn’t just a good idea.
It’s the law.

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A star is in *dynamic equilibrium*: it can survive only so long as it can produce energy in its core.

A star is not a truly stable object.
So why are heavier stars brighter?

More mass $\rightarrow$ more compression

$\rightarrow$ higher temperature

$\rightarrow$ much higher rate of fusion

$\rightarrow$ much higher luminosity

A small increase in mass leads to a large change in luminosity.
If we plot a star’s mass against its luminosity, we find a relation

\[ L \propto M^{3.5} \]

So massive stars are much brighter.
Interlude 2
Measuring the mass of a star

How do we measure the mass of a star?
– using *binaries*.

If we know the period and separation of the binary, we can use Newton’s laws to derive the masses of the stars:

\[ m_1 + m_2 = \frac{4\pi^2 r^3}{GT^2} \]
There are three types of binaries:

- **Visual binaries**: very wide binaries where we can actually see the two stars moving around one another.

  Castor (α Geminorum) is a visual binary with a separation of a couple of seconds of arc. The binary has not yet completed one 467-year orbit since the first observations were made in 1719.
– *Spectroscopic binaries*: where we see the Doppler shifts of the two stars as they move around each other.
- **Eclipsing binaries**: where we see the light from the stars change as one star moves in front of the other.

![Diagram of eclipsing binaries](chart.png)
After the main sequence

How long a star can burn hydrogen on the main sequence depends on two things:

– how much hydrogen it has; and

– how fast it burns it

Like calculating how long a tank of petrol is going to last, you need to know both how much fuel you have, and how fast you consume it.
Thus the lifetime of a star goes like

\[ t \sim \frac{M}{L} \sim \frac{M}{M^{3.5}} = M^{-2.5} \]
This explains the shape of the HR diagrams for clusters: the more massive stars leave the main sequence earlier, so the main sequence gets progressively eroded, like a candle burning down.

last star on the main sequence gets cooler and dimmer (= less massive) as the cluster ages.
What happens when the star runs out of hydrogen in its core?

The star is no longer producing the energy which counteracts gravity.

Gravity takes over again, and the core starts to collapse.
The star becomes enormously large and red: a *red giant*. The core continues to contract, until the temperature becomes hot enough to ignite helium.

This halts the collapse for a while, as the star burns helium in its core, just as it burnt hydrogen on the main sequence.
The cycle then repeats itself. Helium is fused to carbon and oxygen in the star’s core, but eventually the core runs out of helium. Fusion stops, and the core resumes its collapse. This heats up the layer of helium just outside the core, which begins fusing in a shell of its own, inside the hydrogen burning shell.
This extra energy forces the envelope to expand again, and the star begins a second ascent of the giant branch: the **asymptotic giant branch**.
We can predict what happens next: the cycle repeats again and again, each time starting to fuse heavier and heavier elements to stave off the next collapse. The core reaches high temperatures by converting gravitational energy into thermal energy.

Each time the star runs out of fuel, the inexorable collapse due to gravity begins again.
Here, our story splits into two different endings.

– *Low mass stars* (like our Sun) never get hot enough to ignite carbon in their cores. So once the hydrogen is all burnt, the outer layers are ejected and the core collapses to form a *white dwarf*. 
The ejected outer layers are seen as a planetary nebula, an expanding shell of gas lit by the white dwarf within.

The Helix nebula, NGC 7293.
Many are spherical, but there are some spectacularly beautiful examples of other shapes. The Cat's Eye nebula, NGC 6543.
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MyCn 18, an hourglass nebula
As the outer layers of the star are removed to expose the hot core, the star becomes much bluer. Once the core, now a *white dwarf*, has shrunk to its final size, it just cools down.
A white dwarf maintains itself against the gravitational pull because of *degeneracy pressure*.

Two electrons cannot occupy the same energy level, so as the gas becomes very dense, all the available energy levels are occupied.

The white dwarf can maintain itself against the pull of gravity indefinitely.
High mass stars (greater than about 6 solar masses) continue to burn all elements up to iron.

After iron, however, there is no more energy to extract from fusion. Once the silicon in the core has fused to make iron, the star can no longer support itself against collapse.
The star zig-zags across the Hertzsprung-Russell diagram.
The energy released in the supernova explosion is so vast that the supernova can outshine a whole galaxy.
The explosion ejects material into interstellar space, including not only stellar material, but also elements formed during the explosion. This material expands for thousands of years as a *supernova remnant.*
When fusion stops, the iron core, now weighing about 1.4 times the mass of the Sun, collapses inwards again. The electrons are forced to combine with protons to form neutrons. Now the force of gravity is being resisted by the strong nuclear force: in essence, the whole core is like one giant atomic nucleus!

A *neutron star* has been born.
This is the third state of matter we’ve seen to resist gravity:

In **planets**, gravity is resisted by intact electron shells of ordinary atoms (normal matter).

Mean density: $10 \text{ g/cc}$

In **white dwarfs**, electrons are forced so close together that they become rigid; their electromagnetic repulsion resists gravity (electron degeneracy).

Mean density: $10^8 \text{ g/cc}$

In **neutron stars**, neutrons are forced into virtual contact, and the strong nuclear force resists gravity (neutron degeneracy).

Mean density: $10^{14} \text{ g/cc}$
Just as white dwarfs have a maximum allowed mass, so do neutron stars. There comes a mass when even the outward pressure provided by degenerate neutrons cannot counterbalance the inward pull of gravity. And after that, there is no force left which can balance it. Gravity has won: the star must collapse to a black hole.
Finding black holes is difficult...
In fact, we find black holes by using binary systems again. If we find a star orbiting an invisible object which is too massive to be a neutron star, it must be a black hole.
So there you have it. The study of the observed properties of stars leads to profound insight into the nature of stars, how they live and die, and points to the over-arching importance of gravity.
A note on last year’s HSC paper

Question 30 (continued)

(c) The diagram below is a comparison of the spectrum of quasar 3C 273 and a spectrum from a light source on Earth.

(i) From this comparison, identify the feature of the quasar spectrum that is representative of the spectra produced by quasars. 1

(ii) The spectra above are both examples of absorption spectra.

(1) Account for the production of a star’s absorption spectrum. 2

(2) Describe how a spectrum from a star can provide information on the surface temperature of that star. Give a specific example to illustrate your answer. 2
Quasars do *not* have absorption spectra: they have *emission* spectra.

The lines are shifted from their rest wavelengths: quasars are all at high redshift.