John Johnson (2014), *Warm planets orbiting cool stars,* Physics Today, Vol. 67, Issue 3, p. 31

The article can be accessed at https://physicstoday.scitation.org/doi/10.1063/PT.3.2309
During the COVID-19 pandemic, you can access the entire Physics Today back catalogue for free just by registering. You'll need to register (just requires an email address) to get the PDF of this paper.

You can also download the Cornell notes template for this paper (which includes the same questions) as a Word Document or PDF. Teachers, feel free to download this and forward it on to your students.

This week we're looking at another, different style of article. This is a popular science article but for a specialist physics magazine: Physics Today. The magazine is published by the American Institute of Physics and is aimed at physics specialists but to broaden their picture of the research that is taking place in different fields, so each article allows for a broad audience but gives enough detail to keep specialists interested. This makes it the perfect magazine for us, as keen physicists in training.

We're going to move forward with our Harvard notetaking too, by making the notetaking more in keeping with how you might use it in a lecture. Rather than questions down the left-hand column, I'm just going to give you some shorter prompts. These will often be definitions. For each section, I'll then write one or two summary questions.

As a little bit of extra help, this link gives a nice guide to the basic techniques used for exoplanet detection: https://www.planetary.org/explore/space-topics/exoplanets/how-to-search-for-exoplanets.html

INTRODUCTION

$M_\odot$ is the symbol use for a solar mass (the mass of the Sun).	
(P1, C1&C2) *Red dwarf*	A type of star that emits in the infrared part of the spectrum. They are generally smaller than the Sun in terms of mass and radius (they have masses between 0.1 and 0.5 solar masses) and are significantly less luminous (as luminosity scales as M^4). But they're very numerous, and 70% of the stars in the Milky Way are red dwarfs.
(P1, C1) R*adiative diffusion*	The name given to the process of energy transfer from a star's core to the surface.
(P1, C1) *Hydrostatic equilibrium*	The situation in which the forces on the star are balanced. The inwards pull of gravity on the star (from itself) is balanced by the pressure gradient caused by the nuclear reactions (which is trying to expand the star).
(P1, C1) *Luminosity*	The power output (amount of energy transfer per second) from the surface of a star.
(P1, C1) Luminosity scaling with mass.	Luminosity scales as the fourth power of a star's mass.
(P1, C2) *Black body*	An idealised body which can absorb (and emit) radiation at all wavelengths. Contrast this to an element which can only absorb radiation

(P1, C2) *Exoplanet*	Any planet which orbits a star that is not our own. To be a planet, an object must: orbit a star, be in hydrostatic equilibrium, dominate its orbit.

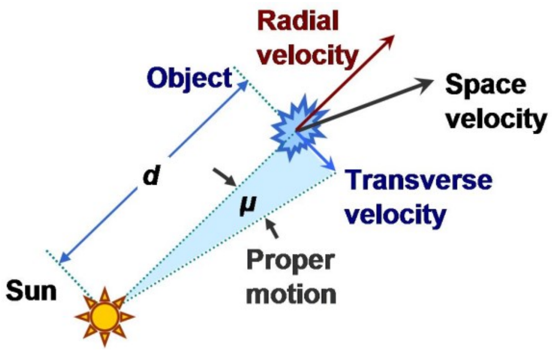
INTRODUCTION SUMMARY QUESTIONS

Why are red dwarfs significantly fainter than the Sun?	Because whilst their masses are between 10% and 50% of the Sun, the luminosity scales as M^4. As $0.1^4=0.0001$ and $0.5^4=0.0625$, the luminosity of red dwarfs ranges between 0.01% and 6.25% that of the Sun.
Why have astronomers focussed their attention on sun-like stars when looking for exoplanets rather than red dwarfs?	Two reasons: Sun-like stars are more luminous so observations are easier and we're interested in finding planets like Earth, and looking around Sun-like stars would give us a planet closest to what we know.
What information can you extract from the graph shown in Figure 1 (take note of the unusual x-scale).	Red dwarfs have masses less than 0.6 $M_{\odot}$. There are significantly more red dwarfs than sun-like stars. As you look at lower masses, we see more and more stars. The distribution is not perfect but samples stars in a generally small region of the universe.

EARLY DISCOVERIES

(P2, C1) *Barnard's star*	The fourth nearest star to the Sun, at a distance of about 6light-years away. It's red dwarf with a mass of 0.144 $M_{\odot}$.
(P2, C1) *Light year*	A unit of distance. It is equivalent to the distance that light can travel, in a vacuum, in a period of one earth year. 1 light year = 9.4607×10^{12} km (nearly 6 million million miles)
(P2, C1) *Proper motion* (HINT: really think about the diagram at this link)	The stars in the sky are not stationary, despite constellations looking fixed. The proper motion is the angular rate that an astronomical object appears to move across the sky from our point of view. It depends on how far away it is and the component of the object's velocity that is perpendicular to the line joining the object to us.
(P2, C1) Van de Kamp's wobbles	The apparent wobbles in the motion of Barnard's star made Van de Kamp think it was being pulled by its orbiting planets. Further observations showed that the wobbles were erroneous, due to systematic errors in the measurement of position.

This image may be useful for some of the ideas in P2, C2



Taken from Wikipedia https://en.wikipedia.org/wiki/Proper_motion

(P2, C2) *Plane of the sky*	A plane that is tangent to the celestial sphere and perpendicular to your line of sight.
(P2, C2) *Doppler shift*	The apparent shift in wavelength of any wave when the emitter and receiver are in motion relative to one another. If they are moving away, we have red shift (the wavelength increases: light shifts towards the redder end of the spectrum, sound becomes lower in pitch). If they are moving towards, we have blue shift (wavelength shortens: light shifts towards the blue end of the spectrum, sound becomes higher pitch).
(P2, C2) *Spectral lines*	Lines in the electromagnetic spectrum that correspond to specific wavelengths of light. Each atom has a specific 'fingerprint' of spectral lines due to the energy levels that the electrons can move between. As the energy levels are discrete, only certain wavelengths of light can be absorbed (and emitted) by each atom or molecule. We can use emission/absorption spectra to identify atoms.
(P2, C2) Does Barnard's star have planets orbiting?	Observations of its motion suggest (both direct observations of its motion in the plane of the sky and of its radial motion compared to us via Doppler measurements) suggest that it is not wobbling due to the gravitational pull of planets.
(P2, C2) *Gl 876*	A red dwarf with a mass of $0.3M_{\odot}$ that is around 15 lightyears from us. It is the first red dwarf discovered to have planets orbiting it via Doppler measurements.
(P2, C2) *Astronomical unit*	The distance between Earth and the Sun. It's a useful unit for comparing the orbits of planets around their stars. 1au = 150 million km.
(P2, C2) *Gl 876b and Gl 876c*	Two planets that orbit the red dwarf *Gl 876,* found from the Doppler shifting of spectral lines on *Gl 876* showing its motion relative was being altered by gravitational effects.

	Gl 876b is a gas giant with twice the mass of Jupiter. *Gl 876c* is another gas giant has a mass of 0.7 Jupiter masses. Their orbital periods are both less than 100 days.
(P3, C1) *Protoplanetary disc*	A dense, rotating disc of dust and gas around a star that might eventually form the planets of the star's solar system.
(P3, C1) *Super earth*	Exoplanets with masses greater than Earth but less than that of Uranus and Neptune. The term does not imply a rocky makeup and many so-called super-Earths are in fact gaseous – the terms *gas dwarf* and *mini Neptune* are also used.
(P3, C1) *Observational bias*	When our measurement technique itself is biased towards finding certain objects. For example, our eye has an observational bias towards stars that emit visible light.

EARLY DISCOVERIES SUMMARY QUESTIONS

Why do astronomers need to use two different techniques to measure the velocity of an astronomical object through the universe?	As the distances and speeds are so disparate to our everyday experiences, measuring velocities is not simple. In the 'plane of the sky', we can measure the velocity of an astronomical object as we see it move amongst other objects in the sky. We can use the technique of parallax to measure how distances change over time in the plane of the sky. But, if an object is moving away from or towards us (or has a component in this direction), we don't detect this in the movement in the plane of the sky. Here, we use Doppler measurements to see how spectral lines are shifted in the light coming from the object.
How do astronomers use spectral lines?	They compare the spectral lines from an astronomical object to the spectral lines from atoms on earth. As stars contain Hydrogen and Helium, the spectral lines from a star should look the same as lab samples of hydrogen and helium. Any shifts are due to the relative motion of the star and us.
How are planets detected around red dwarfs?	Through precise Doppler measurements of the velocity of the star to see the wobbles that occur due the gravitational pull of the planets on the star.
Why are gas giants rare to find orbiting red dwarfs?	Because red dwarfs tend to have low mass protoplanetary discs. Gas giants tend to form around dense, rocky cores that accumulate gas over time. If no such rocky cores exist, then gas giants can't form and

	this seems to be the case, typically, for planetary systems surrounding red giants.

MICROLENSING

(P3, C1) Curving of spacetime	Massive objects (any object with mass) curves space and time around itself. For most objects, this gives no noticeable effect, but for larger objects like stars and galaxies, they can dent spacetime in such a way as to even affect the path of light. We looked at this somewhat in Week 2 when we considered LIGO. This video gives a great visualisation of the curving of spacetime.
(P3, C2) *Microlensing* (this GIF might help. It's also helpful to think of it in terms of brightness, I find).	A form of gravitational lensing in which the light from a background source is bent by the gravitational field of a foreground lens. We therefore receive more light than we would have done, either by seeing multiple images (that may be significantly distorted) or, if the alignment is right, an Einstein ring.
(P3, C2) *Einstein ring*	The effect of gravitational lensing under conditions of perfect alignment where the observer, lens and source are in a perfect line. As the light from the source is bent in all directions by the lens star, we see a ring formed as the image.

MICROLENSING SUMMARY QUESTIONS

What happens to the brightness of a source star as a lens star moves across our line of sight?	When the lensing is in effect, the brightness increases. The lens object acts to bend more light to our observation. Once the lens star moves out of the way again, so that the light is no longer affected by the perturbation in spacetime, the brightness decreases again to the original level.
How might a planet, if placed in a fortuitous position, alter this lensing by the lens star?	Some of the 'lensed light' caused by a lensing star may pass by planets of the lensing star, this creates additional lensing events and an additional sudden increase and decrease in the brightness – see this link.
Why is the microlensing technique biased towards finding heavier planets?	As the degree of additional lensing from the exoplanets will depend on the level of spacetime curvature and hence the mass of the exoplanet. The more massive the planet, the greater the additional lensing effect and the easier it is to detect.

TRANSITING EXOPLANETS

(P4, C1) *M Dwarf*	Name given for Earth-sized planets that orbit red dwarf stars.
(P4, C1 & C2) Transit method	By monitoring the brightness of a star, if a planet intersects our line of sight to the star then it will block some of the light, leading to a reduction in brightness (related to the size of the planet). The dips in brightness will come at regular intervals as the orbit of the planet remains stable.
(P4, C1) GJ 1214 and GJ 1214b	GJ 1214 is a red dwarf star 39 light-years from Earth. GJ 1214b is a super-Earth planet that orbits GJ 1214,
(P4, C2) *Habitable zone*	The region around a star where water can exist in its liquid state. The region is not too close to the star so as to boil the water, and not too far away from the star so that the water freezes.

TRANSITING EXOPLANETS SUMMARY QUESTIONS

Why is an earth sized planet easier to detect if orbiting a red dwarf?	A red dwarf is a smaller sized star. The dip in light is proportional to $\left(\frac{R_P}{R_*}\right)^2$ so if the star is half as big, then the dip in light will be four times larger.
Why is it easier to detect planets in the habitable zone around red dwarfs than sun-like stars?	It is easier to detect planets that are close to stars using the transit method. The habitable zone of red dwarf stars is very close to the star, whereas the habitable zone around sun-like stars is much further away. This allows the transit method to easily detect planets that are more likely to harbour liquid water.
(You'll need to read part of the next section to answer this). What are the downsides of using ground-based telescopes to find exoplanets with the transit method?	The atmosphere of the Earth varies in its transparency, so our measurements of brightness are hampered, meaning that ground-based techniques only see larger dips in brightness from stars. Additionally, when the Sun is in our line of sight to the star, the measurements are obviously useless.

KEPLER'S RED DWARF CENSUS

(P4, C2) *Kepler space telescope*	A space telescope used for detecting Earth-sized planets via the transit method.
(P4, C2) *CCD*	Charge coupled devices are high quality image sensors

KEPLER'S RED DWARF CENSUS SUMMARY QUESTIONS

What advantages does Kepler have over ground-based methods?	It collects more photons and is therefore more precise. It can operate for 24hours a day, unhindered by weather conditions.
Why can Kepler make more accurate measurements of the transits of planets around brighter stars?	As there are more photons from the brighter stars. The more photons there are, the more accurately you can determine any changes that occur.
What difficulty do red dwarfs present when hunting for planets?	As red dwarfs are smaller and dimmer, it is hard to accurately determine their radius. The radius of the star is needed to accurately determine the radius of any orbiting planets.

STELLAR SPECTRA

(P5, C1) *Absorption lines*	An atom can absorb photons that have an energy equal to any of the differences in energy of electron energy levels. This gives each atom or molecule its own absorption signature as electrons jump between very different energy levels. If we sent an entire spectrum of light through a gas (e.g. hydrogen), only the photons corresponding to the discrete energy level jumps would be absorbed and the rest would pass through unencumbered. If we detect this spectrum afterwards, we will see dark lines – the absorption lines – at energies corresponding to the absorption events.
(P5, C2) *Parallax measurements*	Measurements of the apparent movement of an astronomical object relative to 'background stars' when the earth is at opposite sides of its orbit around the Sun allow us to estimate the distance to the object.
(P5, C2) *Metallicity*	The abundance of elements heavier than hydrogen or helium in an object. These elements aren't necessarily metallic at all, but *metal* is astronomer short-hand for "elements heavier than H or He".

STELLAR SPECTRA SUMMARY QUESTIONS

Why are the properties of red dwarfs not as well understood as sun-like stars?	We have studied the Sun extensively so can make easy comparisons between the Sun and similar stars. The absorption lines of red dwarfs are not well understood and without a comparison to the Sun to rely on
How do astronomers deduce the mass of a red-dwarf?	There is a correlation between the luminosity of red dwarfs in the infrared part of the spectrum and their mass. As the luminosity is the total power output of the star, but we can only measure the

	received power on earth, we need to know how far away the red dwarf is to calculate its luminosity. You can imagine this similarly with a light bulb and a light meter. The light bulb has a fixed power output (its 'luminosity') but, the further away we are from the bulb, the dimmer it appears to us – this is because the power is spread out over a larger and larger sphere as we get further away.

A MINIATURE

(P6, C1) *Kepler 42*	A small, red dwarf star that has three small planets orbiting it, all with small orbits and short orbital periods.

A MINIATURE SUMMARY QUESTIONS

What does Figure 5 show?	The size distribution of planets around red dwarf systems, whose orbital periods are less than 150 days. On average, red dwarf systems have 2 planets. The planets are more likely to be smaller (between 0.5 and 1.5 times the earth's radius). And there are fewer and fewer planets as we look for larger planets. Out of more than 100 similar red dwarf systems, only one contained a planet as large as Jupiter.
What do studies of red dwarf systems suggest about Earth-like planets?	The data suggests that, on average, there should be one Earth-sized planet in the habitable zone for every two red dwarf systems.

FROM HUNTERS TO GATHERERS SUMMARY QUESTIONS

Why will the next generation of planet hunting instrumentation likely be tailored towards the infrared portion of the electromagnetic spectrum?	As red dwarf systems seem to host a large proportion of earth-sized planets in their habitable zones (0.5 such planets per red dwarf on average). As red dwarfs are more luminous in the near-IR, new instrumentation will likely focus on this.
How will astronomers look for life on planets they think have potential?	They'll look at absorption spectra from the red dwarf to see the superposed atmospheric features of the planet's atmosphere as it transits the star. These features will be compared to samples of elements and compounds on Earth to understand which elements/compounds are present in the planet's atmosphere.

SUMMARY QUESTIONS (submit these, along with your SKIM-READ answers to thomas.millichamp@warwick.ac.uk)

Why do you think red dwarfs are such an interesting area of research?

Discuss the different ways in which astronomers use spectral lines.

Compare the techniques of microlensing and transit photometry for finding exoplanets.

FURTHER READING

NASA have an entire website devoted to exoplanets at https://exoplanets.nasa.gov/

Our very own Dr. David Brown has created a workshop that includes loads of links to tools to enhance what we've looked at here https://warwick.ac.uk/fac/sci/physics/research/astro/people/dbrown/transitworkshop/

The article mentions the TESS experiment towards the end, you can learn more about that here https://tess.mit.edu/

If you are interested in learning more about exoplanets, there are some great popular books on exoplanets (e.g. The Planet Factory: Exoplanets and the Search for a Second Earth by Elizabeth Tasker) and I've been given a list of textbooks by Professor Dan Bayliss if you would like something that is at a truly advanced level:

- How Do You Find an Exoplanet? (Princeton Frontiers in Physics) by John Johnson (the author of the paper this week)
- Transiting Exoplanets by Carole Haswell
- Exoplanets (Space Science Series) by Sara Seager