Einstein's Triumph

Humility ultimately vanquished arrogance, this time. Einstein might not have received the prize for his contributions to relativity theory, but he was soon able to have these celebrated in spite of the Academy. Einstein learned of the Academy's decision in a telegram that reached him while he was en route to Japan. He was relieved to receive the prize. He had been counting on it since 1918. At a time of decreasing value of the German Mark, he needed a hard currency to make alimony payments in Swiss Francs for his ex-wife and children living in Zurich. But he also was tired of being asked by journalists and others why he had not already received a Nobel Prize. It was the money that attracted him. Although he never expressed any special reverence to the Nobel Prize, Einstein later told a Swedish journalist that the prizes brought about a "social regulating" of age-old injustices. "Through the prizes scientists finally can harvest dividends from their work just like businessmen." And that made him happy.

Providentially, his trip to Japan would keep him away from the formal ceremonies of December. He could avoid the stiff formalities and media attention, both of which he loathed. Einstein undoubtedly found amusing the instructions informing him that when he delivered his Nobel lecture, he must lecture on the topic for which he has been awarded the prize: viz., no relativity. He arranged to hold his Nobel lecture the following summer. And he went not to Stockholm and the Academy, but to Sweden's second city, Gothenburg, where he addressed the 17th Congress of Scandinavian Natural Scientists. Not being a formal Nobel ceremony, Einstein felt free to choose the topic for his lecture, or simply did not care. He spoke on recent developments in relativity theory. Sitting in the front row of the audience was one most attentive spectator who let it be known that he very much wanted to learn something of relativity theory: King Gustav Adolf Vth. On later occasions when Einstein drew up lists of his most important honours, he did not include the Nobel Prize. ■

About the author

Robert Marc Friedman is professor of history of science at University of Oslo. He acknowledges support from the National Science Foundation for research on the Nobel prizes. His publications include Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology and The Expeditions of Harald Ulrik Svedrup: Contexts for Shaping an Ocean Science. His play "Remembering Miss Meitner" was performed at Gothenburg Theatre, Swedish Broadcasting's Radiotheatre, and elsewhere, including at the 2004 International Nuclear Physics conference in Gothenburg. Another play, "Becoming Albert Einstein" opens in August in Bergen.

Further Reading

Full references to archival documents used in this summary can be found in:

Robert Marc Friedman, "Nobel physics prize in perspective", Nature, 292 (1981), 793-98.

Friedman, "Text, context, and quicksand: Method and understanding in studying the Nobel science prizes", Historical Studies in the Physical Sciences, 20 (1989), 63-78.

Friedman, The Politics of Excellence: Behind the Nobel Prize in Science (New York: Freeman/Times Books, 2001), Chapter 7.

Abraham Pais, "Subtle is the Lord....": The Science and Life of Albert Einstein (Oxford: Oxford University Press, 1982), Chapter 10.

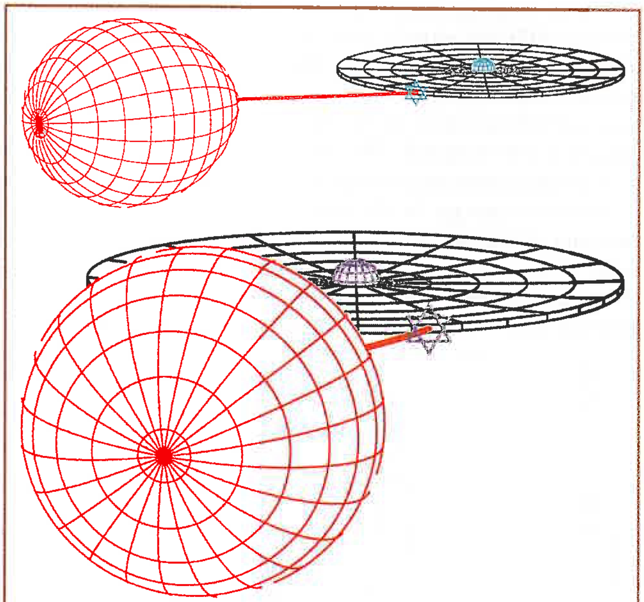
Doppler Tomography

Tom Marsh,
Department of Physics, University of Warwick, Coventry CV4 7AL

Flattened disc-like structures are common throughout the Universe whenever matter has accumulated, for instance in the formation of stars and galaxies. Studies of these discs and related structures have benefited over the past two decades from an indirect imaging technique based upon medical Xray imaging called Doppler tomography. As will be described, this allows us to probe physical scales far below the reach of even the largest current telescopes.

Accretion

The Earth and other planets will continue to orbit the Sun until the Sun itself becomes a red giant some 7,000 million years hence. The outer planets and possibly the Earth too will survive beyond even this point as the Sun evolves to its final state as a small, dense star called a white dwarf. Although attracted towards the Sun, the planets never fall into it because they have angular momentum, and there is nothing, short of a passing star, that can remove it[1]. How then can the Sun and other stars ever have formed given that they had to coalesce from rotating clouds originally much larger than the Solar system?



▲ Fig. 1: Schematic pictures of a mass-transferring binary star with an accretion disc. A cool, tidally-distorted star (red) loses mass at the saddle-point in potential between the two stars. The gas forms a disc around the small hot, companion (blue). The compact star, the disc and the spot where the transferred matter hits the disc dominate the luminosity of these systems. The entire system shown here is comparable in size to the Sun; they have orbital periods which range from 10 minutes to 10 days.

[1] This is not quite true: gravitational radiation removes angular momentum, but so feebly as to be negligible over the lifetime of the Sun.

features

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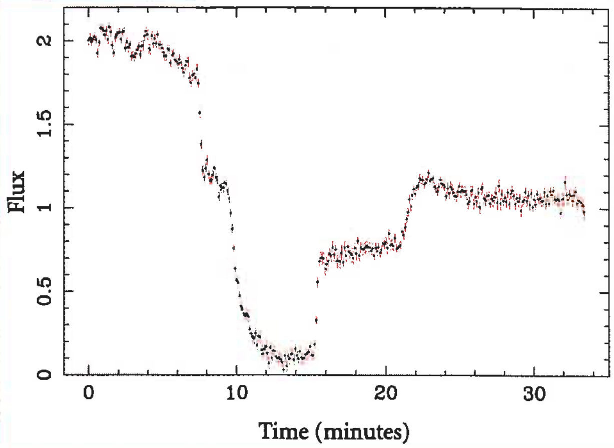
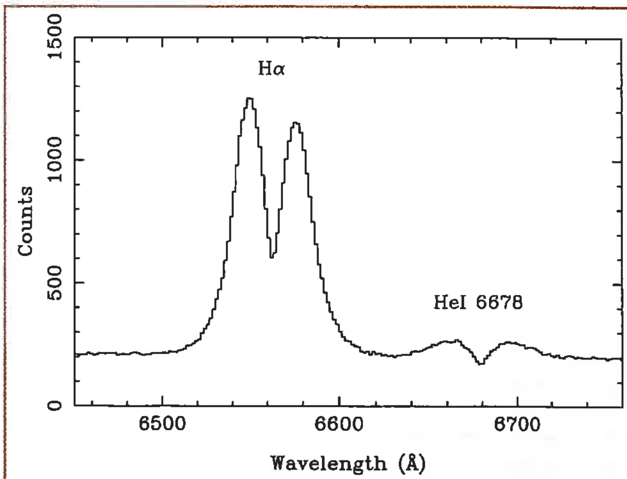


▲ Fig. 2: The brightness versus time during the eclipse of an accreting binary star shows two sharp drops as first the accreting star (a white dwarf) and then the impact region of the gas stream and disc are eclipsed, followed by sharp rises as the white dwarf followed by the bright-spot emerge from eclipse [3].

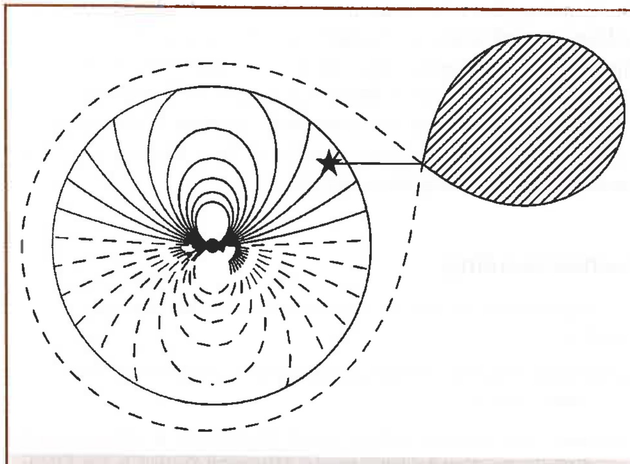
The problem is one of the re-distribution of angular momentum which needs to be removed before matter can accrete onto a compact object whether it be a forming star or a black-hole. Nature's solution, in many, although not all, cases is an accretion disc, a flattened structure in which material orbits on near-circles around the central object. Interaction between different annuli, traditionally ascribed to "viscosity", although in fact it is probably the result of magnetohydrodynamic turbulence [1], allows angular momentum to be transported outwards in the disc while causing the matter to execute a slow in-spiral. This allows accretion to occur, and as a by-product generates energy from the release of gravitational potential energy. In the case of accretion onto the most compact objects of all, neutron stars and blackholes, 10% or more of the rest mass energy of the accreted material can be released as radiation (by comparison, nuclear fusion in stars liberates only ~1% of the rest mass). Accreting black-holes in our Galaxy can produce over a million times the power of the Sun, with most of the energy coming from the inner few tens of kilometres of the disc, and almost entirely radiated at X-ray and γ-ray wavelengths. Accretion onto the super-massive black-holes, 10^8 or more times the mass of the Sun, that sit at the centres of many galaxies powers sources another factor of a million or more brighter still. Many millions of such sources, enshrouded in dust, are thought to produce the X-ray "background" that is seen from all parts of the sky.

Some of the most easily studied examples of accretion discs are to be found in close pairs of stars in which material flows from one star to its companion (Fig. 1). The discs in these binary systems are small, having outer radii ranging from 0.1 to 10 solar radii, compared to the several thousand solar radii of proto-planetary discs and those surrounding the super-massive black-holes. This makes the "viscous time-scale" on which the disc responds to variations in the mass supply rate accessible to observation. The viscous time-scale at radius R in a disc is given by $t_\nu = R^2/\nu$, where the kinematic viscosity $\nu = \eta/\rho$ is the ratio of the viscosity η to the density ρ of the material of the disc. Rather general arguments [2] suggest that the kinematic viscosity has an upper limit given by $\nu < c_s h$, where c_s is the sound speed and h is the thickness of the disc, which for discs supported by gas pressure is given by $h \sim (c_s/v_K)R$, where v_K is the Keplerian orbital speed at radius R. Thus the viscous time-scale is subject to the limit $t_\nu > (v_K/c_s)R/c_s$; observed values are typically at least a factor of 10 higher than this limit. In the region of the disc from which the Earth formed $v_K \sim 30\text{kms}^{-1}$, $v_s \sim 1\text{kms}^{-1}$ and $R \sim 1.5\text{x}10^8$ km, leading to $t_\nu > 100$yr, while in the outer parts of a disc in a close binary $v_K \sim 600\text{kms}^{-1}$, $v_s \sim 10\text{kms}^{-1}$ and $R \sim 5 \times 10^5$ km, giving $t_\nu > 1$ month. Thus in close binary discs it is possible to see complete cycles of changes, for instance between faint and bright states, and it is the study of these discs that has driven many theoretical developments in the field.

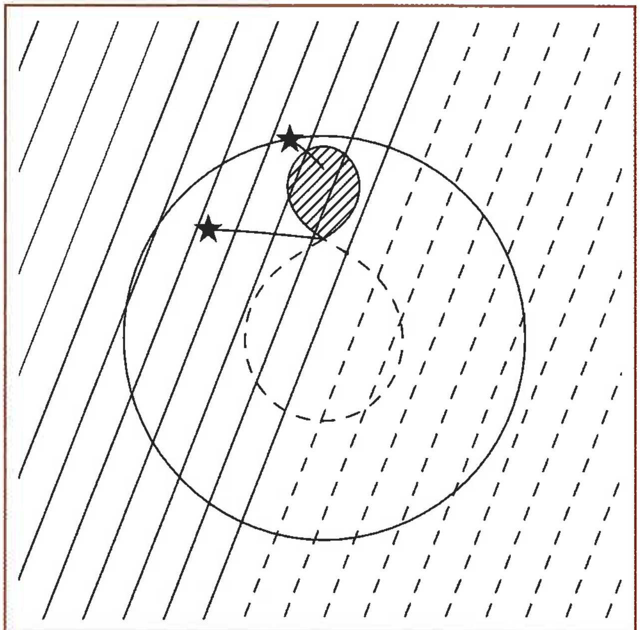
The accessible time-scales in close binary stars come at a heavy price: they are not directly resolvable. Nearby examples are about 200 light-years away and are comparable to the Sun in size (~ 10^6 km). They therefore subtend ~10^{-4} seconds-of-arc at the Earth. To resolve them well would require a



▲ Fig. 3: Atomic emission lines from an accretion disc. The lines are very broad (equivalent to ~ 4000kms^{-1}) owing to Doppler shifting from the surface of the disc. The two peaks come from the outer disc and are a classic signature of emission from discs.



▲ Fig. 4: The figure shows the dipole-field pattern made by lines of equal radial velocity over a disc in Keplerian rotation with $v \propto R^{-1/2}$. The observer is assumed to be located on the right-hand side of the figure. Solid lines represent material moving away from Earth while dashed regions move towards it.



▲ Fig. 5: The figure shows the equivalent of Fig. 4 in velocity rather than position coordinates. The lines of projection become straight. Since by the definition of the coordinate axes the mass donor star moves in the positive y direction, in velocity coordinates it appears on the positive y axis. Emission from the disc appears outside the circle which represents the outer edge of the disc; the inversion is a result of Keplerian $v \propto R^{-1/2}$.

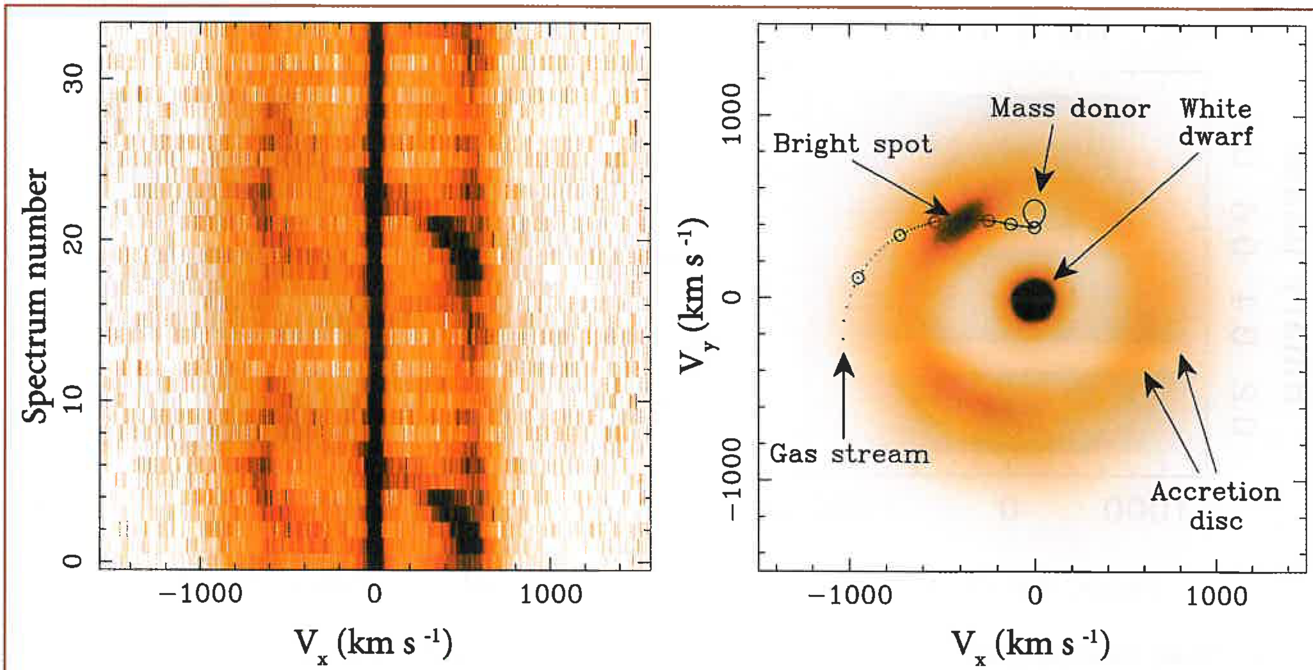
diffraction-limited optical telescope of about 10km diameter, beyond the wildest dreams even of astronomers. We have then had to turn to indirect imaging techniques for trying to unravel the nature of the discs and other structures within these stars.

Eclipse Mapping

The principle behind indirect imaging is to exploit information upon the spatial distribution of emission that may be encoded within the spectra or light curves (brightness versus time) of the systems. The right-hand panel of Fig. 1 suggests one such method. When suitably oriented, binary stars may eclipse, and during the eclipse the accretion structures may be eclipsed. For instance when the accreting star is eclipsed, sharp edges appear in the light curve because it is small (see Fig. 2). For a given geometry one can readily deduce the location within the system of the sources of the sharp drops, which for instance can allow one to measure the ratio of the stellar masses from dynamical arguments about the flow of the transferred matter. This can be extended by modelling the brightness distribution over the disc as a 2D array of delta functions, with the light curve serving to fix the relative contribution of each point source. This is the principle of the "eclipse mapping" method developed by Keith Horne [4].

Doppler Tomography

The main contribution of eclipse mapping has been to measure the temperature distribution versus radius over discs, providing a fundamental test of theory because the temperature distribution is largely determined by energy conservation. Eclipse mapping is however limited for imaging. A useful way to see why this is so is to consider the nature of the information available: as one enters eclipse, over a short interval of time a thin strip of disc along the leading edge of the occulted region goes into eclipse causing a drop in flux. During a whole eclipse we therefore effectively measure a series of line integrals of the brightness. On emerging from eclipse, another series of projections is obtained at a different angle. Such series of line integrals are called "projections". In this case the 1D derivative of the light curve contains two projections at different angles of the 2D brightness distribution of the disc. A series of projections can be used to reconstruct the higher dimensional distribution that they originated from using a



▲ Fig. 6: The left panel shows spectra plotted in row-by-row with time running upwards over one cycle of an accreting binary. The right-hand panel shows the equivalent Doppler image in velocity space with features marked. Dots along the stream mark steps on 1% of the distance from the accretor to the start of the stream; circles mark steps of 10% (courtesy Danny Steeghs).

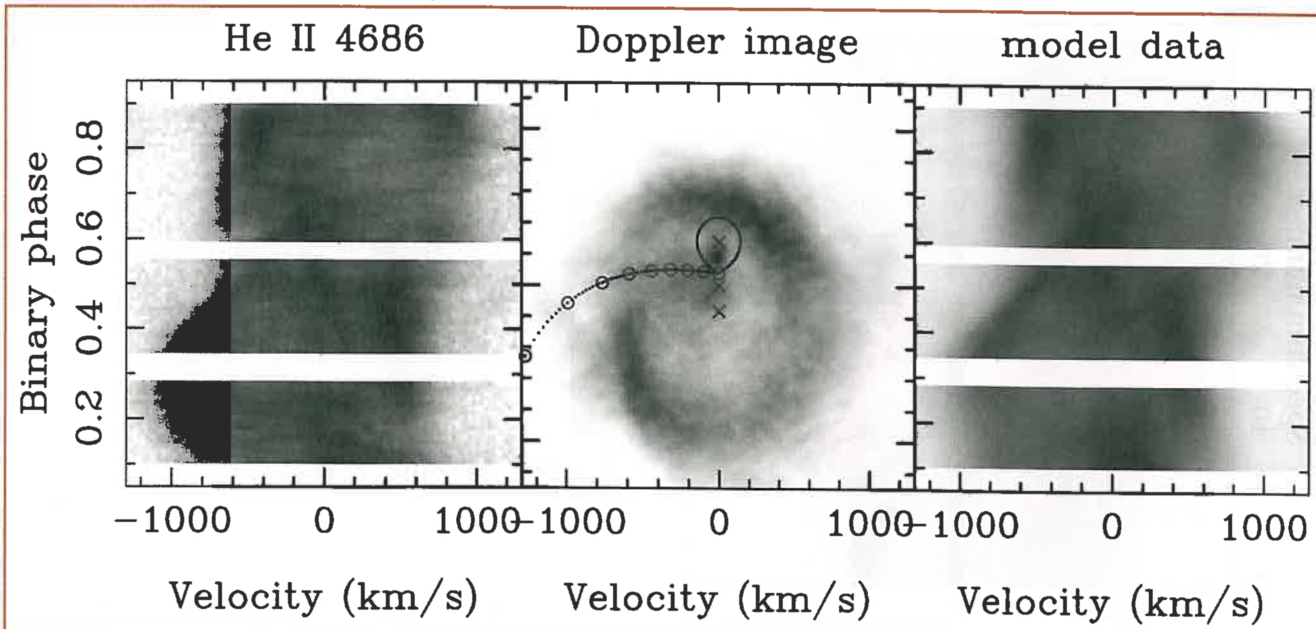
process known as "tomography" (see the special box on tomography). Eclipse mapping is a case of "limited-angle tomography" and with just two angles, we cannot hope to obtain perfect reconstruction.

Doppler tomography is an alternative indirect imaging method based upon atomic line emission such as Balmer series lines which are emitted strongly by accretion discs (Fig. 3). In this case we can obtain many angles and reliable images can be obtained. The bulk flow speeds in discs, which range from 600 kms^{-1} in the outer disc to over 2000 kms^{-1} in the inner disc, are greatly in excess of other broadening mechanisms such as thermal broadening (~ 10 kms^{-1}). This means that the line profile retains an imprint, albeit scrambled, of the distribution of emission over the disc. For instance, emission 2000 kms^{-1} from line centre can only come from the inner disc. The formation of the line profile is in fact another form of projection, with the 2D atomic emission distribution giving a 1D profile as a function of radial velocity (component of velocity along the line-of-sight). To see why, consider Fig. 4 which shows lines of equal radial velocity at a particular point in the orbit of a binary. Regions of the disc which lie between adjacent radial velocity contours all have a similar speed along the line of sight v, and therefore they contribute to a single part of the line profile at wavelength $\lambda \approx \lambda_0(1+v/c)$ where λ_0 is the rest wavelength and c is the speed of light. For instance the two peaks of Fig. 3 come from the largest complete crescent-shaped regions of Fig. 4, i.e. the largest regions unaffected by the outer edge of the disc. Therefore the atomic line profiles are effectively the result of integration over the curved strips of Fig. 4. This process is what is meant by a projection.

Fig. 4 shows just a single phase in the orbit. At other phases, the binary rotates but the dipole-like pattern stays locked in the observer's frame. Relative to the binary, the lines of projection rotate, and so by observing multiple orbital phases, we obtain the equivalent of the multiple projection angles used in medical tomography. The analogy with computerised tomography can be made even more plain with a transformation of coordinate system. Fig. 5 shows the equivalent of Fig. 4 as seen in velocity rather than spatial coordinates. Viewed in these coordinates, the lines of projection become straight. Velocity coordinates do not rely on assumptions such as the flow being Keplerian, and it is standard to use them.

Tomography

Tomography refers to the process of constructing a spatial distribution of physical quantity given measurements that are essentially line-integrals ("projections") through the distribution. This crops up in many different fields. For instance, the travel-times of seismic waves, $t = \int dl/C_s$ where C_s is the sound speed, is used in "seismic tomography" to map the sound speed within the Earth, which can help identify changes in composition. Perhaps most famously, in medical tomography, the absorption of X-rays by a specimen is directly related to the line integral of the opacity through it because if a beam has initial intensity I_0, then it will emerge with intensity $I = I_0 \exp(-\tau)$ where τ is given by the line integral $\tau = \int \kappa(x)dx$ and $\kappa(x)$ is the absorption/unit length at position x along the path of the X-rays. If this is measured over a series of parallel lines at each of a series of angles, a 2D slice of the specimen can be built up, the trick being to use the multiple measurements of τ to determine κ over the two dimensions of the slice. This is the idea behind CAT scanning. Fig. 9 illustrates how projections can reveal something about the nature of the higher-dimensional distribution 5 from which they originate. In this example there are just three projections, but they nevertheless reveal useful information about the object. One generally requires many (>20) angles to build up an accurate image. The mathematical inversion goes under the name of the "Radon transform".



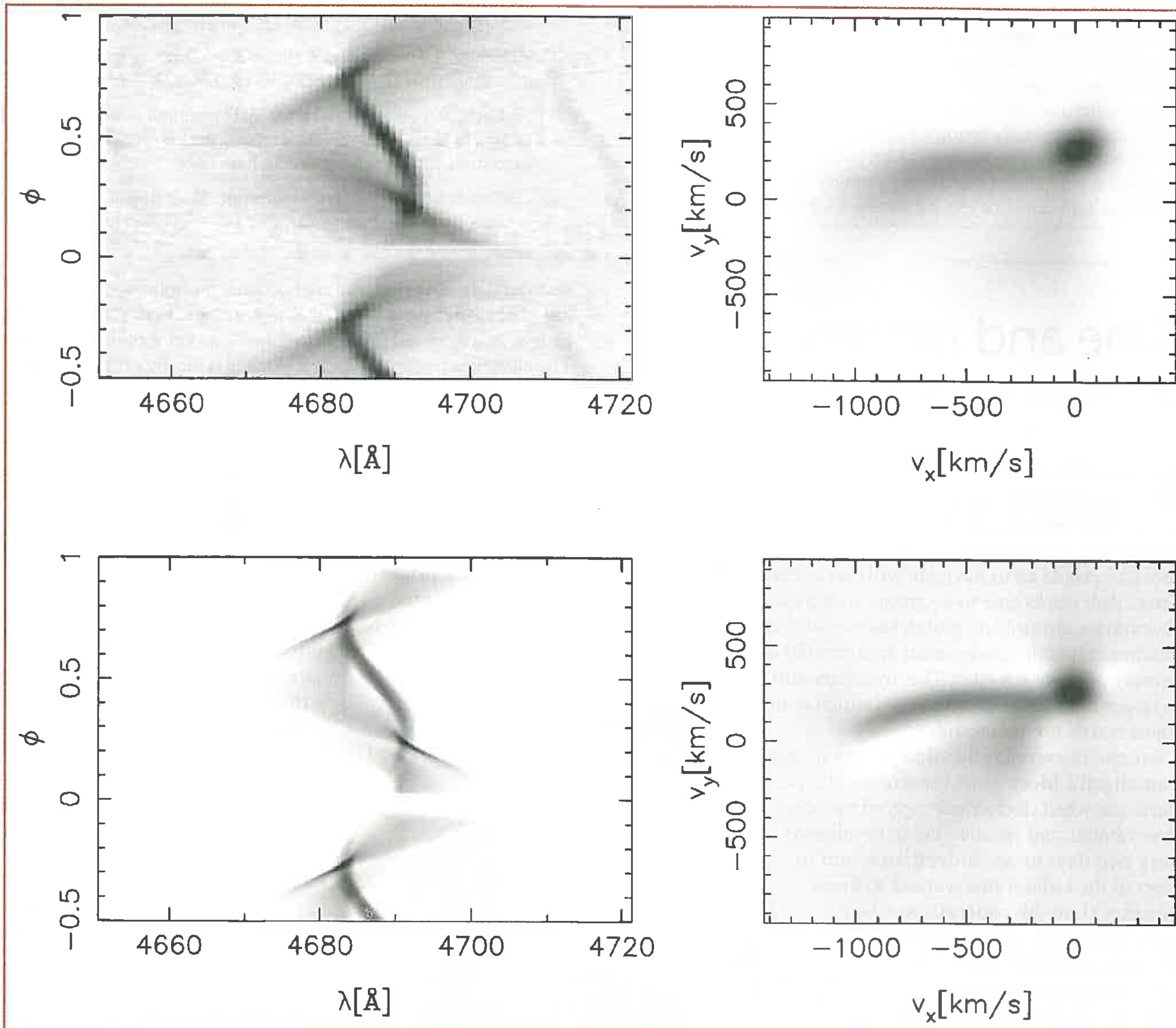
▲ **Fig. 7:** The left panel again shows spectra plotted row-by-row with time running upwards over one cycle of an accreting binary. The middle panel shows the equivalent Doppler image in velocity space. Apart from the strong narrow emission from the inner face of the mass donor, the most obvious feature is the very asymmetric background from the disc which takes the approximate form of a loose two-arm spiral. The right panel shows artificial data computed from the middle panel showing the recovery of many of the peculiar features seen in the data. Figure from [7].

Fig. 6 shows a real Doppler image of a system that shows several features in a clear form. The disc appears as the smooth ring with a radius of ~ 600 kms^{-1}, representing the orbital speed in the outer disc. An intense spot is seen at one location on the ring that corresponds to the impact of the stream of transferred material with the disc. Its location shows that the disc extends 70% the distance from the white dwarf to the point where the stream leaves the mass donor. Somewhat unusually, this system displays emission from the accreting white dwarf, seen as the almost-straight line running upwards in the left panel and as the strong central spot in the right panel. Plotted over this image are the predicted locations of emission from the mass-transfer stream and the mass donor which, as we will see, is sometimes visible in Doppler images.

Since the method of Doppler tomography was presented [5], it has been applied in over 200 papers. Doppler tomography has elucidated the dynamics of the interaction between the mass transfer stream and disc and the distribution of line emission over the disc. Perhaps the major discovery that Doppler tomography made possible was the discovery of spiral structures in accretion discs [6] (Fig. 7) While there had been theoretical speculation about spiral structure in discs in the 1980s, they had never been recognised in data. In this case Doppler tomography proved essential in unravelling the complex changes in line profiles that the spiral structures cause. Although they undoubtedly owe their origins to tidal effects, the precise nature of the spiral structures in these discs remains controversial.

Doppler tomography has also proved useful in systems in which a strongly magnetic white dwarf (surface field ~ 5000 T) prevents the formation of any disc at all, resulting instead in magnetically-controlled streams of matter. Fig. 8 show a beautiful example which can be modelled as a free stream of matter gradually being stripped of material as itapproaches the accretor and the magnetic field becomes ever more dominant.

The exciting prospect for future application of Doppler tomography is to build up "time-lapse" movies to study how discs change over the viscous time-scale. This is primarily an observational challenge, but the first steps are being taken towards achieving it. ■



▲ Fig. 8: The top-left panel shows spectra from a system dominated by the magnetic field of the accretor, plotted over 1.5 orbits. The top-right shows the Doppler image. The lower panels show an empirical model in which mass is stripped from the mass transfer stream as it nears the accretor. The bright spot in the images is from the X-ray irradiated face of the mass donor. Figure from [8].

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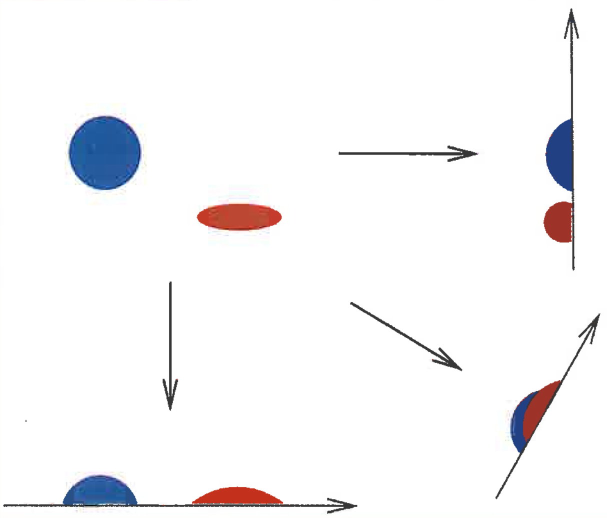

▲ Fig. 9: The process of forming projections is illustrated with a simple object consisting of two discrete parts, blue and red. Three angles of projections are shown. Knowing the projections angles and the projections, one could deduce the positions of the blue and red objects and that the red one was horizontally elongated. This is an elementary form of "tomography". The identification of the positions of these objects is very analogous to the location of the small sources that the light-curve of Fig. 2 makes possible.

About the author

Tom Marsh received his PhD from the University of Cambridge in 1986. He is now the holder of a PPARC Senior Fellowship and Professor of Experimental Physics and head of the Astronomy & Astrophysics group at the University of Warwick.

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Time and money

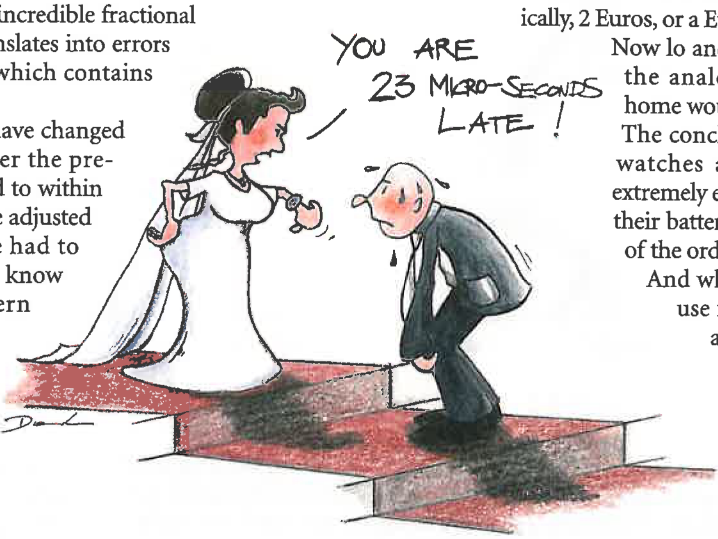
L.J.F. (Jo) Hermans, Leiden University, The Netherlands

Back in 1905, when Einstein was working on relativity in which 'time' plays such an important role, he would have never guessed that time would be measured with such an astonishing accuracy just a century later. As an example, think of GPS satellite clocks: to enable us to navigate with accuracies on the order of meters, their clocks have to be precise within nanoseconds. And in laboratories around the globe, laser-cooled Cesium and Rubidium fountain clocks reach an incredible fractional accuracy of about 6×10^{-16}. This translates into errors no larger than 20 ns in one year (which contains almost exactly $\pi \times 10^7$ seconds).

But also in everyday life, things have changed dramatically. Most of us remember the pre-quartz era, when clocks rarely agreed to within a few minutes, and watches had to be adjusted every two days or so. Indeed, one had to resort to the radio if one wanted to know the exact time. By contrast, modern quartz clocks and watches routinely have accuracies better than 1 in 10^6: some 30 seconds in a year. And, except for the switch-over to daylight saving time, adjustment is rarely necessary.

At what cost, in terms of kWh and Euros, do we read our daily time so accurately? The electrical energy consumption, even for an analog clock operating on 230 V in our home, is very small of course, as we can tell from the negligible amount of heat released. The electrical power for such a clock is typically on the order of 1W, and since a year has about 10^4 hours, it consumes about 10 kWh per year. In terms of money, that's about a Euro per year.

Now let us look at our digital watch. It typically operates on a silver oxide battery of 1.55 V having a charge of roughly 25 mAh. If we assume that the battery runs for at least two years, a back-of-the-envelope calculation shows that the watch operates on a power of less than 2 microwatt. That is very little indeed: it is six orders of magnitude more efficient than an analog clock connected to the mains.



What about the cost? Such batteries cost, typically, 2 Euros, or a Euro per year of operation. Now lo and behold: isn't that what the analog counterpart in our home would cost?

The conclusion is simple. Digital watches are very accurate and extremely efficient. But the energy in their battery is extremely expensive, of the order of 50 000 Euros/ kWh. And whatever type of clock we use for knowing the time as accurately as we do, the cost is 1 Euro at most for an entire year. If Einstein were alive today, he would probably agree: that's a lot of time for very little money. ■