increase in image diameter will be small. The change in central intensity is relatively larger and provides a sensitive and conceptually useful indicator of image quality.

Calculations of telescope-induced degradation of image quality are easily carried out if the MTF is available. It is interesting to note that the effects of aperture diffraction alone can be calculated in this way once the atmospheric MTF is determined. Figure 5 shows curves of $(MTF)^2$ for average and good seeing, diffraction by a 1 metre aperture and for the aberrations of a telescope mirror just meeting a typical modern specification. Figure 6 shows the relationship between R (the ratio of central intensities after and before degradation by the telescope) and telescope aperture, for average and good seeing. The curves are plotted for diffraction only and for telescopes with aberration corresponding to the typical specification. From figure 6 it is clear that at small apertures and in average seeing, aberrations are responsible for only a minor part of the telescope-induced image degradation. For larger apertures and good seeing the telescope aberrations are more important and it could be argued that the specification used is appropriate for small apertures but is not sufficiently stringent for larger telescopes.

The principal advantage of the use of MTF is the simplicity of the calculations needed for reliable derivation of the image quality of a complete system, which can include the atmosphere, telescope aperture and aberrations. Measurement of MTF for large mirrors does not appear to present any major difficulty since any test method capable of producing reliable wavefront-height data can give the MTF. To produce data of high accuracy in the spatial frequencies of greatest interest (those where the atmospheric MTF is appreciably greater than zero), some revision of test details may be needed. Calculation of central intensity via MTF provides a simple method of expressing image quality, and the ratio of the central intensities of the system (atmosphere + telescope) to that of the atmosphere alone, provides a numerical measure of optical performance that is practical, easily visualized and appropriate to the conditions of use.

Neutron Stars

E. J. Zuiderwijk

It is a common trick among astronomers who give popular lectures to shock the audience with large numbers. The statement that a matchbox of material from a white dwarf weighs as much as several large locomotives (or elephants if there are influential ecologists present) is always of great effect. But that is all antique by modern comparison. Now, one cubic millimetre of a neutron star (about the size of the head of a pin) weighs one million tons! Dr. Ed Zuiderwijk of the ESO Scientific Group in Geneva is engaged in a theoretical and observational study of these incredible objects. There is still much to be learned from them, both for physicists who look for the ultimate properties of matter and for astronomers who wonder how stars end their life.

Neutron stars are among the more exotic objects in the sky. Their mass is comparable to that of our sun, but their diameter is as small as 15 kilometres. The matter in these stars is therefore extremely dense—the density is of the order of 10^{18} kg m^{-3}—and is mainly composed of degenerate neutrons, thus making the star look like a giant atomic nucleus.

The prediction that neutron stars should exist was made by the famous physicist Landau in 1933, immediately following the discovery of the neutron as a constituent of the atomic nucleus. It took, however, more than 30 years before they were discovered. Direct evidence for their existence was found in 1967 when the first radio pulsar was detected. This kind of objects turned out to be rapidly rotating neutron stars. The widely-accepted idea is that they originate from supernova explosions where in a final collapse of the stellar core the exploding star comes to the end of its evolution. With only one (or possibly two) exceptions all neutron stars, appearing to us as radio pulsars, are found to be single, isolated objects. An accurate, direct mass determination for many of these compact stars is therefore not possible.

The discovery of X-ray binaries with the UHURU satellite in 1970 revealed, however, that neutron stars also occur in binary systems. In such a system the neutron star is orbiting a "normal" star, the latter being often detectable from ground-based observatories. The X-rays are produced when kinetic energy of infalling gas is converted into heat at the surface of the neutron star. This matter originates from the "normal" optical star; the mass transfer occurs either because this star overflows its Roche lobe or loses mass by means of a stellar wind. The gravitational potential at the surface of the neutron star is very large (as the stellar radius is very small) and causes the gas to arrive with a velocity of up to one half of the velocity of light ($=3.0 \times 10^8$ m sec^{-1}). Subsequently the gas is heated to a temperature of about 10^7K, which is high enough for the gas to radiate strongly in the X-ray region of the spectrum.

Mass Limit

Theoretical models predict the existence of an upper limit to the mass of a neutron star, above which no stable configuration can exist. A compact object more massive than this upper limit is expected to collapse completely, presumably to become a black hole. The numerical value of this mass limit can be computed from a neutron-star model; the result depends, however, on which particular model is used. To be more specific, the choice of the so-called "equation of state", which describes the relation between the physical quantities pressure, temperature and density of the degenerate nuclear material, is of crucial importance. For such extreme conditions as prevailing inside a neutron star, the equation of state cannot be measured in present-day laboratory experiments and has to be inferred from theoretical nuclear physics. Scientists, however, do not agree which equation of state has to be chosen. Therefore, the predicted numerical values for the limiting mass as computed from several realistic neutron-star models range from 1.4 to about 2.7 solar masses.

Which specific model is the correct one? This question is not likely to be solved in the near future either by improvements of the theory or by more laboratory experiments. Therefore, one way to extend our knowledge about neutron stars—and about matter at nuclear density in general—is to measure directly the masses of these compact objects. Until now only the neutron stars in X-ray binaries offer the opportunity to do so.

Mass Determination of X-ray Binaries

The masses of the two components in a binary system can be computed if we know the absolute dimensions of both orbits in which the stars revolve around their common centre of mass.

It happens that in several X-ray binaries the X-ray source is also an X-ray pulsar. In that case the observed X-ray intensity is regularly pulsed, which is directly connected with the rotation of the neutron star around its axis (just like in the case of the radio pulsars; the mechanism which produces the radiation is, however, completely different). Observed pulse periods are in the range of 0.7 second to 14 minutes. The arrival times at the X-ray satellite of these regularly emitted pulses are affected by the orbital motion of the X-ray source. They can therefore be used to determine the orbit of the neutron star. At present the orbits of seven of these X-ray pulsars are known: Cen X-3, SMC X-1, 4U0900-40, 4U1538-52, 4U1223-62, Her X-1 and of 4U0115+634.

The orbit of the optical counterpart can be determined in the classical way by measuring the radial velocity variations of this star from the small Doppler shifts in the apparent wavelength of well-chosen absorption lines in its spectrum. This, however, turns out to be a challenging problem. The optical counterparts are generally faint: only two of the well-established X-ray binaries are brighter than 7th magnitude (HD153919/1700-37 and HD77581/0900-40) whereas the counterparts of Cen X-3, SMC X-1, 4U1223-62 and Cyg X-1 are of 9th to 14th magnitude. In order to obtain a reliable estimate of their orbits, one needs high-dispersion spectrograms in the range of 10Å/mm to 40Å/mm and this requires a lot of observing time for the fainter stars. Furthermore, the optical spectra of some X-ray binaries are contaminated by strong emission features, distorting the shape of the absorption lines. An accurate velocity measurement is then very difficult, if not impossible. This is for instance the case with the spectra of Be stars such as X-Per (0352+309) and HD102567 (1145-62) or of the Of star HD153919 (1700-37). Fortunately, among the optical counterparts there are several early-type supergiants for which a sufficiently accurate velocity determination can be made.

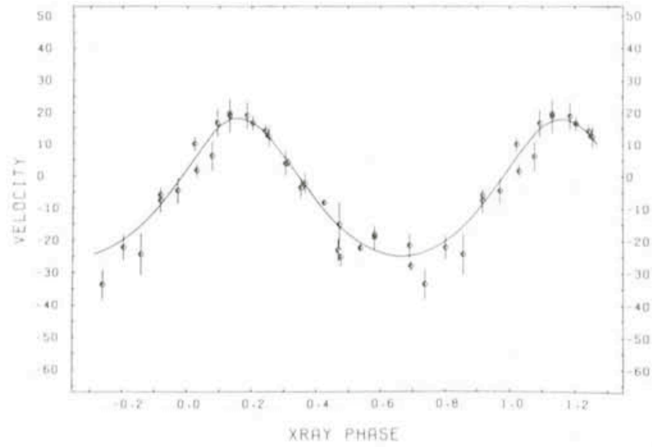
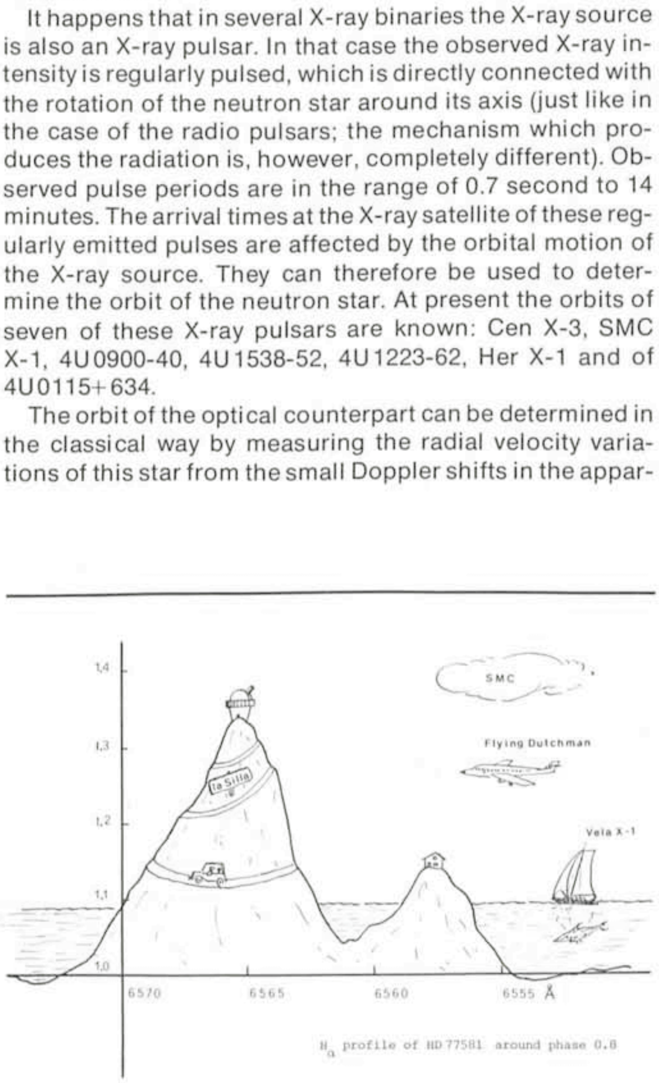


Fig. 1: *Radial velocity variations of HD77581 as a function of binary phase. Phase zero corresponds to mid X-ray eclipse time. The continuously drawn curve represents the best-fit solution to the data.*

The X-ray binary HD77581/0900-40 is illustrative for the number of spectrograms needed to obtain a satisfactory accuracy of the determined mass. The orbit of the B0.5Ib supergiant HD77581 was determined by Dr. Jan van Paradijs and his colleagues from the University of Amsterdam (1977, *A&A Suppl.* **30,** 195). They used 92 coudé spectrograms obtained with the ESO 1.5 metre telescope on La Silla to measure the velocity variations of this star. The results are shown in figure 1. The orbit of the X-ray source 0900-40 had been established from SAS-3 observations by Rappaport et al. (1976, *Ap. J.,* L. **206,** L103). Combining these two results one arrives at the following relation between the mass of the neutron star M_n and the inclination of the orbital plane *i*:

$$M_n \sin^3 i = 1.67 \pm 0.12 \text{ solar masses}$$

Radial velocity measurements refer only to the motion of the two components with respect to the observer along the line of sight. They tell us, however, nothing about the inclination, the angle between the line of sight and the orbital plane. Therefore, as a final step to arrive at the mass of the neutron star we have to estimate this inclination angle *i* independently. It turns out to be possible to do so through the analysis of photometric variations of the optical counterpart (the "lightcurve"), sometimes in combination with knowledge of the X-ray eclipse duration.



Always in the frontline, THE MESSENGER brings, for the first time—and in stiff competition with other journals—an example of the newest direction in contemporary art. Entitled "Per aspera ad astra", this drawing by J. M. M. van Lith of the modern Dutch school reconfirms the impact of applied astronomy upon other disciplines. From the PhD thesis of Dr. Zuiderwijk.

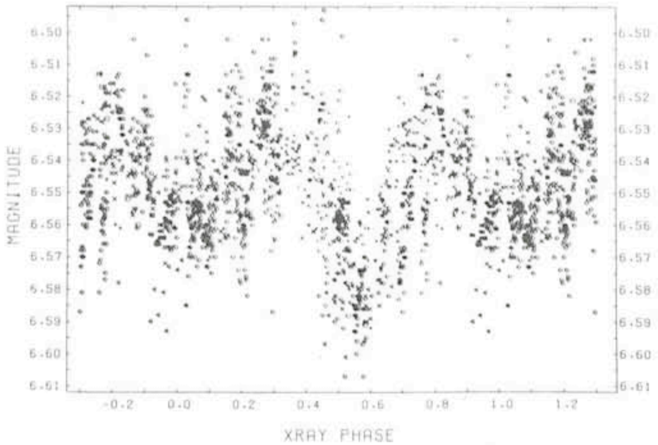


Fig. 2: *Ellipsoidal brightness variations of HD 153919. This V-light curve is composed of approximately one thousand photoelectric measurements obtained by several observers (see also* Messenger *No. 14, p. 8). Clearly visible are the maxima around phase 0.25 and phase 0.75 and the minima near phase 0.0 and phase 0.5.*

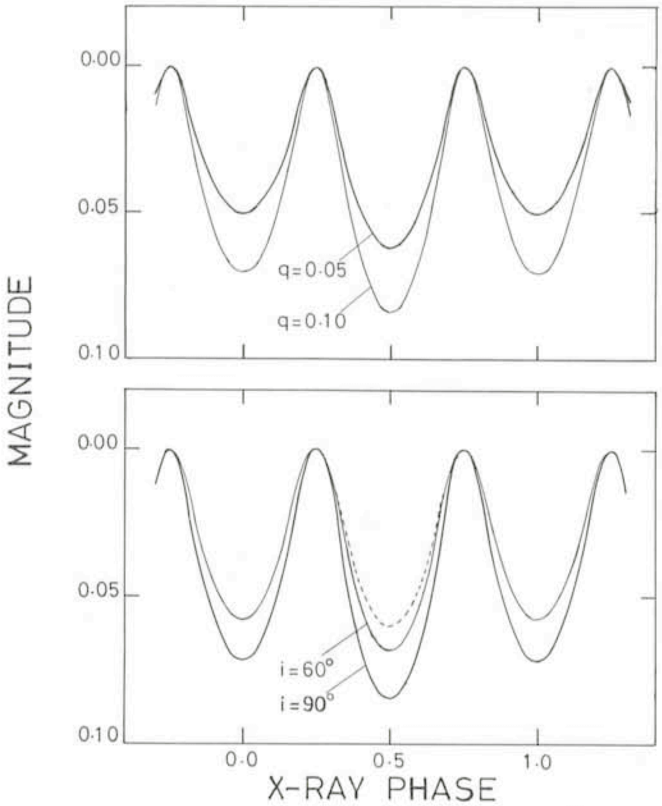


Fig. 4: *Theoretical lightcurves in the Strömgren y passband arising from a tidally and rotationally distorted star of 20 solar masses. The computed magnitude of the star is arbitrarily set to zero at X-ray phase zero.*

Upper part: *The aspect of the lightcurve as a function of the mass ratio q. Both curves are calculated for an inclination angle i=90° while it is assumed that the star fills its Roche lobe completely. A mass ratio q=0.05 corresponds to a neutron-star companion of 1.0 solar mass; a mass ratio q=0.1 to one of 2.0 solar masses. Clearly visible is the increase of the amplitude with increasing value of q.*

Lower part: *These lightcurves are all computed for a mass ratio q=0.1. The continuously drawn curves correspond to a Roche lobe filling star observed with different inclination angles (q0 and 60 degrees). The dashed curve arises from a star which is underfilling its Roche lobe by 5 per cent in radius. This curve coincides around phase zero with the one computed for i=60° and a roche lobe filling star. Notice, however, that the minima in this case are of almost equal brightness.*

Ellipsoidal Variations and Lightcurve Analysis

The lightcurve of the optical companion in an X-ray binary is usually of the so-called ellipsoidal type. It shows in one orbital cycle two maxima of approximately equal brightness and two minima of different depths (figure 2). This is explained by the fact that the star is not a perfect sphere. Tidal forces and rotation produce a slightly elongated shape; in addition, this distortion causes the stellar surface not to be of uniform temperature. The changing aspect—due to binary revolution—results in a modulation of the observed light of the star. Obviously, the more the star is distorted, the larger the amplitude of the variations will be. The most extreme case occurs when the star completely fills its critical Roche lobe.

It is possible to calculate ellipsoidal lightcurves by means of a computer model based on the above given physical "picture". This type of numerical computation is generally carried out as follows. The stellar surface is divided into discrete surface elements, distributed approximately uniformly (figure 3). Each grid element has its own

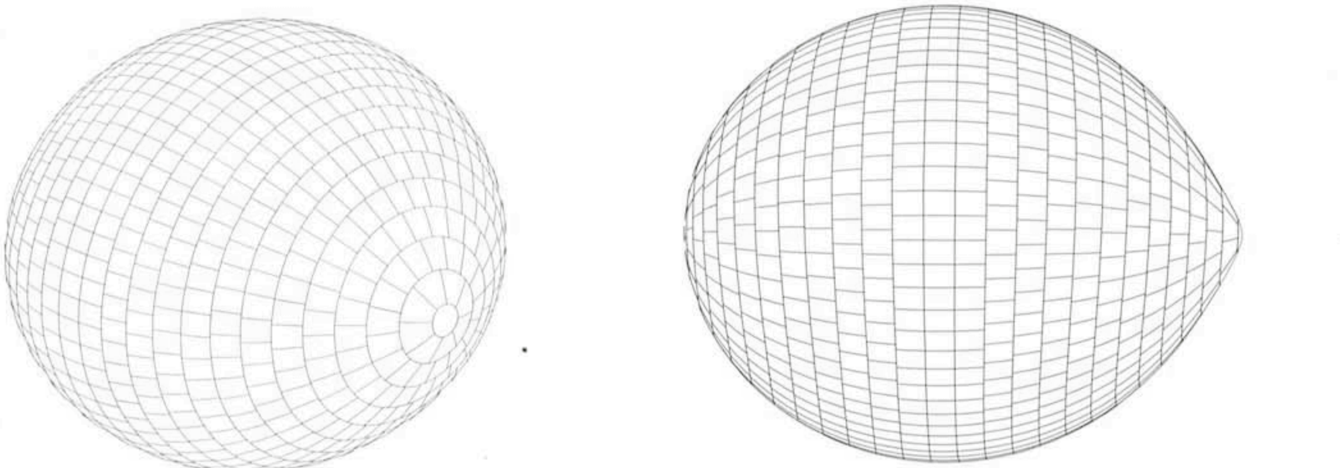


Fig. 3: *The grid of discrete surface elements, as seen from two different directions. A mass ratio q=0.076 was adopted. The optical star fills its Roche lobe almost completely. Notice the elongated shape of the star. The small dot to the right indicates the position of the neutron star.*

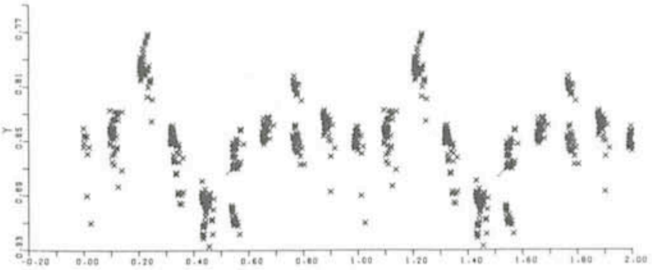


Fig. 5: *The lightcurve of HD 77581 in the Strömgren y passband.*

coordinates, temperature and acceleration of gravity. The radiation emitted towards an observer—situated at a very large distance—is computed by simply adding the contributions from all visible surface elements. A lightcurve is obtained by repeating this final step for different positions of the star in its orbit, with respect to the observer.

In the lightcurve synthesis programme that was developed by the author the local contributions to the total flux are computed using realistic model atmospheres. This programme generates lightcurves for the Strömgren uvby and for the Walraven VBLUW photometric passbands (figure 4). Computations show that the shape of the lightcurve, and in particular the amplitude of the variations, are mainly determined by (1) the ratio q of the mass of the neutron star to that of the optical component (rather than the masses themselves), (2) the ratio r of the mean radius of the star to the binary separation, and (3) the inclination angle i. The parameters q and r determine how much the star is distorted.

In order to find their numerical values in the case of a real-life X-ray binary, we vary these three parameters until an optimal agreement is obtained between the calculated and observed lightcurve of the star.

The value of q is already available for HD77581/0900-40 from the radial velocity and X-ray pulse measurements ($q = 0.076$). Using the amplitude of the lightcurve of this system (figure 5) we were able to derive a reliable constraint for the inclination angle: the value of i is between 75 and 90 degrees, i.e. less than 15 degrees from the line of sight. Therefore, the most probable value for the mass of the neutron star in this system is 1.74 solar masses. It was also found that the supergiant HD77581 almost completely fills its critical lobe.

We would like to apply a similar analysis to the lightcurves of other X-ray binaries, including those systems where q is not very well known. It will be clear that we need very accurate observed lightcurves in order to obtain reliable constraints on the system parameters. From figure 1 it can be seen that many observations are needed to determine an average lightcurve, because of the considerable intrinsic scatter. Therefore, a long-term observing programme is in progress on La Silla to obtain accurate multicolour lightcurves of Galactic and Magellanic-Cloud sources. These observations are made by astronomers from ESO and from the University of Amsterdam with the Dutch 90 cm telescope and Walraven photometer.

Image Processing at the Astronomical Institute of the Ruhr-Universität Bochum

T. Kreidl, M. Buchholz, Ch. Winkler

Image processing of astronomical photographs or, in general, one- and two-dimensional data, play a larger and larger role in the reduction of observations. Several institutes in Europe are acquiring their own hardware and, more recently, an effort to exchange the associated programmes, the software, has been initiated. At the Astronomical Institute of the Ruhr University in Bochum, image processing is already well developed, as explain Drs. T. Kreidl and M. Buchholz together with graduate student Ch. Winkler in this review of the Bochum system.

The Need for Image Processing

Image processing has been in existence now for many years and has been employed in numerous areas before astronomers began to make use of the possibilities offered by its methods. Radio astronomers, having no actual photographs to look at, were forced to turn to numerical methods of handling their data; as the number of observations increased, improved methods became essential to deal efficiently with the enormous number of measurements on hand. Optical astronomers found themselves in similar situations as soon as certain manipulations of their original data became necessary, such as the transformation of densities on a photographic plate into intensities.

When electronic detectors began to come into use, methods had to be worked out to apply geometric corrections, to correct for image defects, and—when no permanent picture was retained—to have the possibility to view and work with the reconstructed image of the digitized data. As fainter and fainter images started to preoccupy the interest of many astronomers, ways to bring out the contrast in objects, remove noisy backgrounds and sum a number of identical images—to mention just a few—became necessary.

In short, an image-processing system should serve to deal with large amounts of pixels in an efficient manner, to work interactively with the image, and provide the means to view, correct, compare and derive meaningful information by utilizing the statistical contents of the measurements to make visible information that would normally remain undiscerned. Obviously, it is not possible to derive more from measurements that is inherently present, and in this regard care must be taken when manipulating data so as to pre-