THOMAS CAWTHRON MEMORIAL LECTURE

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High Speed Photometry

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CAWTHRON INSTITUTE

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The impression usually received from perusal of a textbook or popular account of astronomical knowledge is of the large distances, the great masses and sizes, the huge numbers and the vast timescales that are involved. While such dimensions still provide the fabric of astronomy, in recent years increasing attention has been given to exotic celestial objects of small size and short timescale. Much of the stimulus for this change of outlook has come from discoveries that have resulted from applications of new or improved techniques.

TIMESCALES AND VARIABLE STARS

Timescales of changes in the Universe are principally of two kinds. Evolutionary changes are governed by nuclear processes; the plentiful supply of nuclear energy contained in a star ensures that it has a long life—the Sun, for instance, has not changed its appearance significantly in the past 10^9 years. With few exceptions, phenomena related are not directly observable—they are inferred from studies of objects known to have widely different ages.

However, many of the changes that occur in astronomical bodies are modulated by gravitation. Simple dimensional arguments show that the characteristic time of a process that is gravitationally controlled is given by $T \approx \frac{1}{\sqrt{Gp}}$, where G is the gravitational constant and p is the average density of the system. The *gravitational timescale* is thus $T \approx 4.10^3\ (p)^{-\frac{1}{2}}$ secs where p is expreseed in gm cm^{-3} . Some examples of the use of this elementary equation may be instructive. The average density of our Galaxy has been determined to be $\sim 10^{-24}$ gm cm^{-3} , which implies $T \sim 10^8$ years (i.e. a timescale of the order of the Galactic rotation period); the average density of the Sun-Earth system (the mass of the Sun divided by the cube of the Earth-Sun distance) is $\sim 10^{-7}$ gm cm^{-3} , giving $T \sim 1$ year (the revolution period of the Earth around the Sun); mean densities of cool giant stars are known to be $\sim 10^{-7}$ gm cm^{-3} , which explains why their periods of light variations are ~ 1 year. The mean density of the Sun is $\sim 1\frac{1}{2}$ gm cm^{-3} ,showing that if it oscillated bodily it would do so with a period ~ 1 hour, or alternatively, that it could not spin with a shorter period than about one hour without flying apart. Mean densities of normal stars do not exceed ~ 10 gm cm^{-3} (for the coolest dwarf stars) so we would not expect to find variables with periods of much less than 20 minutes. Our equation applied to the Earth ($\rho \sim 5$ gm cm^{-3}) indicates why its free oscillations, excited by major earthquakes, are observed to have periods $\sim$½ hour.

From these examples of the gravitational timescales operating in some more or less familiar situations, we turn to exotic objects. It has been known for fifty years that a few stars, the white dwarfs, are composed of matter at densities far higher than any achievable in the laboratory. Studies of the ways stars evolve have revealed that white dwarfs represent one of the end products of the lives of stars. Another possible remnant of the life of a more massive star, predicted in the 1940's, is a neutron star. White dwarfs and neutron stars are composed of degenerate material; that is, matter at very high densities in which, in the case of stars, gravitational forces are opposed by "degeneracy pressure" rather than the pressure familiar in ordinary gases.

White dwarfs have mean densities of $10^6 - 10^8$ gm cm^{-3}, and neutron stars $\sim 10^{14}$ gm cm^{-3}. Their expected pulsational periods (or minimum rotational periods) are therefore $\sim 1-10$ secs for white dwarfs and $\sim 10^{-3}$ secs (i.e. one millisecond) for neutron stars. All of the above timescales give approximate values for the *fundamental* periods of oscillation. Stars, as with stretched strings on musical instruments, can also vibrate in overtones with shorter periods. In special cases, we will later see, undertones with longer periods are also possible.

The oscillations of a star produce variations in surface area and temperature which give rise to changes in its total luminosity. Stellar pulsations are therefore usually detected by Photometric methods (in a relatively few cases, variable stars have been discovered by spectroscopic methods). The majority of known variable stars have periods in the range 0.2 – 1000 days and possess large amplitudes of variation. This, however, is almost certainly a selection effect: most variable stars have been discovered through photographic surveys which can reveal only these kinds of variable star. In recent years, more accurate photometry of a few likely candidates (and, on occasions, stars not expected to be variable) have demonstrated the probable existence of large numbers of very low amplitude variables with periods down to 20 mins. Large scale surveys of the required accuracy to detect many such objects have yet to be made.

Pulsations are not the only cause of variability in stars. Many stars are double and produce eclipses if we happen to lie close enough to their orbital planes. Close double stars (those in which the separation between the two stars is so small that significant interaction occurs between them) are particularly prone to variability: in simple cases their distorted shapes, caused by mutual effects, produce variability from the changing aspects as they revolve in orbit. In extreme cases, the tide raised on one of the components is sufficient to remove material from its surface, which then falls towards the companion star. The impact of this turbulent material on the companion (or on gas surrounding the compainion) creates a luminous spot of variable intensity (Figure 1). The contribution of this spot to the total brightness of the double star system also varies around the orbital cycle as a result of the changing aspect with which we view the spot.

All of these processes are gravitationally controlled and their timescales are governed by our simple equation.

OBSERVATIONAL TECHIQUES

Before discussing some of the results obtained from observations of stars in these various categories, a description of observational techniques is required. The variable stars of large amplitude (greater than ~ 5 per cent) and periods longer than a few hours can be observed adequately by techniques that have been available for several decades. These comprise a sensitive detector (a photocell in the early work; photomultipliers in more recent times) in the focal plane of a telescope, with an instrument (usually a chart recorder attached to a resistance bridge) to measure the current from the detector. Such a system is limited in its use by internal noise, slow response and low sensitivity. To such purely instrumental restrictions should be added a limitation faced by all ground-based observations: the atmosphere through which we observe is turbulent. This produces brightness fluctuations (scintillation) with amplitudes ~ 1 per cent (in large telescopes) on all timescales from 1 millisec to seconds. Thus even with perfect equipment it is not possible to detect low amplitude variations without some massaging of the observations.

Over the past fifteen years the sensitivity of detectors has been steadily increased. The introduction of pulse-counting techniques, in which discrimination can be made against much of the internal noise inherent in detectors and in which more efficient measurement is made of the output from the detector, accounts for part of the improvement. At the same time, advances in photomultiplier design have increased their quantum efficiency by factours of four or more. Together, these allow us to observe much fainter stars than hitherto possible.

A further advance was the introduction of on-line mini–computers into optical astronomy. This constituted the crucial ingredient for the study of short-timescale phenomena in variable stars. Work in this field was started at Princeton in the mid 1960's, but the principle efforts were made by J. Hesser and B. M. Lasker at the Cerro Tololo Observatory in Chile, and by the author and his colleagues at the McDonald Observatory, Texas, and more recently at the Sutherland site of the South African Astronomical Observatory. Several advantages arise from the use of a computer to analyse the signal from the photometer. First, the incoming pulses (photoelectrons) may be integrated, for any length of time between microseconds and minutes, and thus any desired time resolution may be achieved, limited only by the pulse rate (i. e. the brightness of the star. With a 100 inch telescope, about 10 photoelectrons sec $^{-1}$ are obtained from a 17th magnitude star). Second, the large amounts of data acquired when using high time resolution are readily handled by the computer. Also, elaborate displays of the data can be provided by the computer, and some on-line analysis performed and the results displayed. These latter facilities are important in evaluating the nature of the information being recorded. Finally, the computer can be made interactive with the photometer, automatically changing filters or other devices.

The output from the on-line computer is in digital form and therefore immediately compatible with the large campus computer needed for a complete analysis of the data. We are therefore able to apply the full range of statistical techniques developed in other fields. For example, we often require to smooth our data (by means of sum-difference filters) in order to remove slow variations or irrelevant high frequency noise. Detection of low amplitude periodic signals, lost in the noise of atmospheric scintillations, requires power spectral analyses (employing the Fast Fourier Transform algorithm), computation of periodograms, or correlation analyses. These , in a restricted manner, can also be performed on-line at the telescope in order to improve our initial assessment of the observations.

EARLY RESULTS

The era of high-speed astronomical photometry started before these new techniques had been developed. In 1954 M. F. Walker, at the Lick Observatory in California, started a photometric survey of the remnants of nova outbursts and stars related to them. Novae are exploding stars which, unlike supernovae, recover more or less completely from their eruption. Several types of novae are known: the classical novae which are known only to erupt once, recurrent novae which explode every few decades, and dwarf novae which erupt at intervals of weeks (but less energetically than the other two types). Some stars have been identified which are spectroscopically similar to these objects (when in their quiescent states) but which are not known to have erupted in historical times. Collectively all of these stars are known as *cataclysmic variables* (CVs).

Walker discovered that the CVs all exhibit rapid light variations: timescales of minutes and amplitudes up to 25 per cent. We now know that all CVs are close double stars and that this non-periodic *flickering* arises from the hot spot formed by transfer of gas. This result, important as it was in demonstrating that CVs must almost certainly contain a degenerate star, was overshadowed by Walker's discovery of persistent periodic brightness variations in DQ Her (the remnant of the explosion of Nova Herculis in 1934). The light oscillations had amplitude of 2 per cent (just detectable above the combined effects of atmospheric scintillation and stellar flickering) and a period of 71.06579 secs. This unprecedentedly short period variable star established the presence of a white dwarf in at least this nova binary and gave added credence to the theory that nova explosions are a result of nuclear ignition of hydrogen-rich gas accreted (from the companion star) onto a white dwarf.

A survey of other CVs failed to reveal any further objects with rapid periodic light variations. One other early result, however, opened a further field of investigation. During a routine photometric survey of white dwarf stars, A. V. Landolt in 1968 discovered that the white dwarf designated as HL Tau$-$76 is variable with amplitudes $\sim$ 20 per cent and a quasi-period of 12½ mins. This was unexpected for two reasons: no (single) white dwarf had been previously detected as variable and the period bears no resemblance to the expected timescale for pulsation.

With the advent of the new techniques, fresh surveys of CVs and single white dwarf stars were carried out at the McDonald, Cerro Tololo and Sutherland Observatories. We shall now abandon chronological discussion and review the results that have emerged from these studies.

VARIABLE WHITE DWARFS

The surveys of white dwarf stars have so far produced twelve variables. We start with a description of the white dwarf designated R548; this has the simplest light curve and perhaps provides the essential clue to the interpretation of the others.

A short portion of the light curve of R548 is shown in Figure 2. Each point represents a 20 sec integration. The amplitude of variation is about 1 per cent, but falls to zero near the middle of Figure 2. This is a beat phenomenon between two pulsations, simultaneously present, with periods of 213 and 274 secs. Power spectra of three different observing runs (Figure 3) show these two periods, but also demonstrate that the amount of power in each of the pulsations varies with time. Extensive observations of R548 (including very long runs commencing at Sutherland and continuing at McDonald Observatory) show that the power in the pulsations varies sinusoidally. The simplest representation of this behaviour is to assume that the 213 and 274 sec pulsations are each composed of two pulsations of very similar period (too close to be resolved in the power spectrum). It is then found that the light curve of R548 is reproduced, to within observational error, by the following four pulsations:

Period (secs)	213.132576	212.768402	274.250813	274.774320
Amplitude (per cent)	0.73	0.43	0.49	0.31

The pulsation periods are remarkably stable: it has been demonstrated that $|dp/dt| < 1 \times 10^{-11}$.

To understand the origin of these two pairs of pulsations in R548 we must briefly consider some basic aspects of the theory of stellar oscillations.

The most obvious way that a star, considered as a gaseous sphere, can oscillate is in the radial direction. That is, waves of compression and rarefaction propagate outwards from the centre of the star, the number of nodes determining the overtone of the pulsation. The period of the fundamental radial pulsation is given roughly by our earlier equation; overtones are of successively shorter period, the ratio between the fundamental and first overtone being typically ~ 1 for white dwarfs.

If a star is rotating rapidly, or if the stimulus for pulsation is not spherically symetric, then non-radial oscillations may be preferred. The quadrupole mode is the simplest to imagine—the star oscillates between a prolate and an oblate spheroid. Higher modes have more complicated patterns of displacement and overtones of shorter period are again possible.

The theory of non-radial motions shows that, unlike radial modes, two complete spectra oscillations occur: the overtones, in which pressure differences supply the principal restoring force, and the undertones, in which the gravity is the principal restoring force. The p-modes are very similar to the overtones of radial motion and decrease in period as the harmonic index increases. However, g-modes behave quite differently; their periods increase as the harmonic index increases—which is why they are sometimes referred to as undertones.

One other feature of non-radial pulsations is relevant here. In analogy with atomic energy levels, in which degeneracy is removed by application of a magnetic field, the non-radial modes have a degeneracy which is lifted by the coriolus force produced by rotation of a star.

Returning to R548, we see that the principal periods are an order of magnitude greater than that expected for radial pulsations. We therefore suspect them to be g-mode undertones. This is supported by the ratio, 1.28, of the periods, which is near the value expected of the quadrupole mode and its first harmonic for a white dwarf star. Furthermore, the close splitting of the two periodicities receives a natural explanation: a rotation period of ~ 1½ days for R548 would produce the observed effect.

Although we have accounted satisfactorily for the observed properties of the pulsations in R548, no adequate theory has been advanced for the driving mechanism of the pulsations. A clue is provided when we turn to the other white dwarf variables. We find that they all have spectral types DA, i.e. they are members of the most populous class of *normal* white dwarfs (there are a large number of white dwarfs which possess abnormal spectra, indicative of peculiar composition and, in some cases, large magnetic fields. None of these is known to pulsate). Furthermore, they exist over only a small range of temperature, a circumstance that leads us to believe that all white dwarfs of normal composition probably pass through the region of pulsational instability as they evolve. This leads us to the conclusion that the white variables are excited by the same mechanism that is operating in the more commonly known radial mode variables (the Cepheids and RR Lyrae variables), though why non-radial modes are preferred in the white dwarfs is still a mystery.

The light curves and power spectra of the white dwarf variables other than R548 show more complexity. This is illustrated in the light curve of HL Tau 76 (Figure 4) and in the power spectra of G29-38 (Figure 5). In this star at least five frequencies are simultaneously present; most of the peaks in the power spectra can be accounted for by *linear combinations* of these principal frequencies. Again we note that the power in any particular periodicity varies with time.

Most of these more complex pulsating white dwarfs have light curves with amplitudes up to 25 per cent, i.e. much greater than in R548. The appearance of linear combinations of frequencies is probably a result of the large amplitude of the pulsations: whereas in R548 the amplitude is small so that the star is oscillating essentially in Simple Harmonic Motion, in the larger amplitude variables the motion is so large that non-linear couplings between modes becomes important.

Very extensive observations of these more complex variable stars will be required before their time-dependent power spectra can be fully charted and interpreted. It is clear, however, that the eventual disentanglement of these remarkable objects will lead to a better determination of the interior structure of white dwarf stars. In this area, modern methods of photometry and data analysis promise rich returns in the understanding of exotic objects.

DQ HERCULES

The 71 sec oscillations in DQ Her (Figure 6) have been studied for a quarter of a century with gradually improving techniques. This very long baseline (of over 10 million cycles) has enabled us to discover that the oscillations are decreasing in period by 26 microsec per year and this decrease is itself diminishing by 0.4μ sec yr^{-1}

DQ Her is an eclipsing system with a period of 4^h 39^m. During eclipse, the 71 sec oscillations diminish in amplitude, disappearing completely at mid-eclipse. This establishes the eclipsed component as the source of the oscillations. From spectroscopic and photometric observations it has been deduced that the white dwarf in DQ Her is surrounded by a large disc of luminous gas–formed by material originating from distorted companion. (In fact, all CV's appear to have such an accretion disc surrounding their white dwarf components). Thus the eclipse in DQ Her is primarily of the accretion disc: the white dwarf itself contributes only a small fraction of the luminosity of the system. The manner in which the 71 sec oscillations change through eclipse can therefore provide a clue to their nature: If they are confined entirely to the white dwarf then they would disappear and reappear rapidly, whereas if they originate partly or wholly in the accretion disc more gradual changes would occur. However, the observations show that the situation is more complicated than this; the oscillations do vary in amplitude slowly through eclipse, demonstrating that the whole accretion disc is involved, but at the same time there is a gradual change in *phase* of the oscillations through eclipse (Figure 7). Several models have been proposed to explain this unexpected behaviour. The most credible at present is that the light variations originate (as required by their short period) in the central hot white dwarf; the ultraviolet pulsed radiation emitted by the white dwarf is absorbed and re-emitted in the visible by the accretion disc. The phase shift during eclipse can be understood if the reprocessed radiation is coming primarily from the side of the disc behind the white dwarf.

The origin of the light variations themselves is still controversial. Either the white dwarf possesses a permanent bright spot which is carried around with a 71 sec rotation period of the star, or the white dwarf is pulsating in a non-radial mode. The gradual speed-up of the oscillations can be explained by accretion of angular momentum and mass from the material spiralling in through the accretion disc.

With the exception of RR Pic (the remnant of Nova Pictoris, 1925), in which the author has one tentative detection (seen on only one occasion, despite frequent observations), DQ Her is the only classical nova remnant which shows periodic oscillations. Why DQ Her is unique in this way is still a mystery.

NOVA-LIKE OBJECTS

Among the nova-like objects, i.e. those stars which are spectroscopically similar to nova remnants and which exhibit rapid flickering, there are three which possess periodic oscillations.

UX UMa is an eclipsing system with a period of $4^h\ 43^m$. Oscillations with a period near 30 secs are occasionally present in its light curve. Apart from their intermittent presence, these oscillations show several other differences from those seen in DQ Her: (a) the period is not constant–it varies between 28.5 and 30.0 secs, with some evidence that the variation is itself periodic on a timescale of weeks; (b) the oscillations do not disappear through eclipse, in fact they stay of constant amplitude and are thus more easily detected during eclipse; (c) a phase shift occurs through eclipse, but in the opposite sense to that observed in DQ Her (Figure 8).

The variable period appears to rule out rotation as the origin of these pulsations; a g-mode oscillation is the only satisfactory explanation. Unlike DQ Her, only a small portion of the disc is eclipsed in UX UMa, which is why the oscillations persist through eclipse. The opposite sign of the phase shift presumably implies that ultraviolet light from the white dwarf is processed by the near side of the accretion disc. These differences between DQ Her and UX UMa will be of ultimate value in modelling the systems and hence in determining the differences between those CVs that have nova outbursts and those that do not.

Another nova-like variable, known as CD -42^o 14462, also shows occasional 30 sec periodic light oscillations, with variations in period. It is a binary with a period of about $4^h\ 45^m$ but does not eclipse. It is almost certainly an object like UX UMa, viewed at a higher angle of inclination.

The third object, AM CVn, shows oscillations with periods near 118 secs, but is also interesting for quite a different reason. In 1967 J. Smak discovered AM CVn to be a variable star with a period of about 18 mins. Spectroscopically it is similar to a white dwarf star, but with peculiarities in its spectral lines. Various explanations were propsed for the 18 min period, but when rapid flickering was discovered in 1971 it became clear that the light curve of AM CVn resembles in all respects that of a cataclysmic variable. The conclusion is that AM CVn is a binary system with a period of only 1051 secs. One of the components is a white dwarf with a mass comparable to that of the Sun; the other has a mass of approximately one hundredth of this. These two stars, revolving in the time taken for an average coffee break, surely constitute one of the most remarkable objects in the sky! Such objects are unfortunately very difficult to discover; there may be many more to be found.

DWARF NOVAE

The frequent outbursts of dwarf novae, during which each brightens by a factor of between ten and a hundred in one to two days and then returns to minimum light at a slower rate, give us opportunities of studying the structural changes that occur during the eruptions. Although the cause of the outbursts is not yet agreed upon, observationally it has been demonstrated that the principal increase in brightness during an outburst originates in the accretion disc. One thoery suggests that matter is stored in the disc until a change of viscosity, or the overwhelming of a magnetic field, allows the material to descend in a rush on to the white dwarf; the energy radiated during the outburst then derives from the gravitational potential energy lost by the accreted mass.

In the surveys of CVs for rapid periodicities it was natural to include dwarf novae in both their quiescent and eruptive states. At the time (1968-71) we had no on-line power spectra facility, so data was collected without any awareness of whether periodicities were present or not. We were certainly able to confirm Walker's earlier results that no *visible* periodicities were present. Most of our initial efforts aimed at interpreting the flickering and general light curves of the dwarf novae; it was not until the beginning of 1972 that we subjected all of our data to power spectra analyses. It therefore caused us great excitement when we found that three dwarf novae (and also UX UMa and AM CVn, discussed above) possessed low amplitude periodic oscillations. Furthermore, these were confined solely to the times of eruption; none of the dwarf novae (with the exception of the abnormal object WZ Sge: see below) show periodicities during their quiescent stages.

Since 1971, systematic searches have been made for periodicities in most of the brighter dwarf novae during eruption. (It is fortunate that the oscillations in general occur when the dwarf novae are brightest, and therefore easiest to observe; as a result, many of the results quoted have been acquired with the use of telescopes of modest size–20 to 36 inches aperture). The results are summarised in Table I, which gives the range of periodicities observed in each dwarf nova.

For each star, there is a fairly narrow range of periodicities; this range is adhered to for each outburst.

Star	**Periods (secs.)**	**Quasi–Periods (secs.)**
SS Cyg.	9.7	32
RU Peg.	11.6 – 11.9	50
Z Cam	16.0 – 18.8	
EM Cyg	16.6	
V436 Cen	20.0 – 20.5	
KT Per	22.5 – 29.5	82 – 147
SY Cnc	23.3 – 33.5	
AH Her	24.1 – 34.8	
CN Ori	24.3 – 33.0	
YZ Cnc	27.0	
Z Cha	27.7	
VW Hyi	28 – 35	~88
RX And	35.7	
U Gem	–	71 – 79

These oscillations are generally present only at, and just following, maximum of outburst (in VW Hyi they are seen only well after maximum). As the brightness of the dwarf nova diminishes after maximum, so the period of the rapid oscillations increases. In the two objects in which oscillations have been seen before maximum, the same correlation exists–a decrease in period as the system brightens (Figure 9). For a given object, the same period is observed at a particular brightness at each outburst, i.e. there is a period-luminosity law.

The range of periods observed, 9 - 35 secs, makes it evident that the oscillations originate in, or near to, the white dwarf component. Two principal theories have been proposed to account for these remarkable oscillations. The first involves non-radial oscillations of the white dwarf, excited by the outburst, the other suggests hot spots rotating in the accretion disc close to the surface of the white dwarf.

The observed duration of the coherent pulsation argues against hot spots (which would become sheared out of existence after a few rotations of the differently-rotating accretion disc). On the other hand, the rapidity with which the periods drift (up to a second an hour) disallows g-mode pulsations of the entire white dwarf. A recent proposal by J. Pringle and J. Papaloizou of Cambridge University has resolved this problem: they show that surface waves (analogues to g-modes, but involving only the outer parts of the star, and designated r-modes) will be excited by the accreted material and these have the correct periods and coherence to match the observations.

Hot spots, however, have been resorted to in order to explain a further set of oscillations recently discovered in dwarf novae during outburst. These are quasi-periodic oscillations, listed in Table I, which have longer timescales than the coherent oscillations. They are called quasi-periodic because although there are cycle-to-cycle variations, the range in period is limited.

One final object should be mentioned. WZ Sge has usually been classified as a recurrent nova because it outbursts roughly every thirty years. However, spectroscopically it is more allied to the dwarf novae and hence has been recently reclassified. This unique object is now known to be unique in another way: it possesses stable coherent oscillations at minimum light, sometimes showing a 27.87 sec period, sometimes at 28.98 sec period, and, on one occasion, both simultaneously. The presence of two periods, despite their long-term stability, argues against a rotational origin. WZ Sge is therefore the only dwarf nova to show full g-mode pulsations, as opposed to the transient r-modes seen during outbursts. WZ Sge is due for another outburst; it will be interesting to see what changes occur in its oscillation periods after the outburst.

The periodicities in dwarf novae that we have discussed by no means exhaust the range observed. Each system has brightness variations modulated by its orbital period (which range from 82 mins for WZ Sge up to 9 hours for RU Peg). Then there are the quasi-periodic outbursts, usually with timescales of weeks. Finally, a few dwarf novae show occasional exceptionally large outbursts, called supermaxima by Frank Bateson, which recur on timescales of six months or more. This variety of timescales, some of which are gravitational, some possibly magnetic or nuclear, accounts for the tremendous interest that dwarf novae have generated in the past decade.

PULSARS

Our final, and most extreme, example of high speed astronomy is in the field of neutron stars. In 1968 trains of radio pulses were discovered, known as pulsars, which were later interpreted as emissions from rotating neutron stars. As the radio positions were improved in accuracy, it became possible to search for optical counterparts of the radio stars. The first, and for nearly a decade the only, pulsar to be detected optically was that in the centre of the Crab nebula. This pulsar, the remnant of the supernova explosion of A.D. 1054, has a pulse period of 33 millisecs–the most rapidly rotating neutron star known. The star itself had been known for many years to be spectroscopically peculiar, but its pulses (30 times a second) were too rapid to have been seen visually. In January 1969, J. Cocke, M. Disney and D. Taylor of Steward Observatory, Arizona, discovered the optical pulsations from this star. Their result was confirmed two nights later by the team at McDonald Observatory.

The Crab pulsar provides an example of the indispensibility of sophisticated electronic techniques in modern optical astronomy. Without these, the details of the light curve could never be known. Despite the faintness of the pulsar (only $\sim$ 100 photons are detected during each cycle, even with the aid of large telescopes), it has been ascertained that the light from the pulsar is substantially linear polarised, and the plane of polarisation rotates rapidly through the main pulse. Figure 10 shows this main pulse, obtained with 20 μ sec integrations, with a total observation time of one hour on the 82-inch telescope at McDonald Observatory. Some idea of the difficulty involved in this experiment can be appreciated when it is realised that in order to allow for the *changes* in apparent pulsar period (caused by the Earth's rotation, the Earth's motion around the Sun and the intrinsic steady increase in period of the pulsar itself), it was necessary to alter the instrumentally generated period (which enabled us to synchronise with the pulsar) in steps of 0.1 nanosecs every few seconds.

The rotation period of the Crab pulsar is considerably longer than the minimum possible for a rotationg neutron star. It is, however, from our timescale formula, much less than the minimum period for a white dwarf–which is one of the principal reasons why pulsars are identified as neutron stars. Our $\sim$ 1 millisec timescale for neutron stars only becomes evident in radio observations of pulsars: radio pulses are found to have substructure which include coherent pulses of $\sim$ 1 millisec period. These have been tentatively identified with oscillations of the neutron star.

According to the theory of emission of radiation from pulsars, their optical luminosity decreases very rapidly as the increase in age and slow down. The shortest period pulsars are therefore the only ones that we can expect to be able to detect optically. A second optical pulsar, the Vela pulsar with a period of 89 millisec, has recently been detected by a group of astronomers using the Anglo-Australian telescope. As no other radio pulsars with comparable short periods are known, it is unlikely that further optical pulsars will be found.

CONCLUSIONS

In this review we have looked at only one area of astonomy in which rapid variations occur. In radio and X-ray astronomy there are many other examples. The discovery of periodic X-ray sources, with periods in the range of seconds to minutes, increases the supply of exotic objects we have available for study. Some of these have also been detected in the optical region. Even without further technological developments, there are many areas of astronomy in which electronic techniques may still be applied. As techniques continue to improve, particularly with the use of high time resolution on large space telescopes, it can be safely predicted that a wealth of new and unexpected periodic phenomena will emerge. Just as the techniques discussed here have revitalised areas that had become stagnant, so improved methods can be expected to uncover even more facets. The astronomy of the 1980's should be every bit as exciting as that of the 1970's.

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FIGURE CAPTIONS

Figure 1. Schematic diagram of a close binary system containing a normal star and a white dwarf.

Figure 2. Short section of the light curve of the white dwarf R548. Each point is a 20-second average of the photon counting rate.

Figure 3. Power spectra of three different light curves of R548. The sharp peaks show the presence of periodic variations in the light curves. Small peaks arise from atmospheric scintillation and are not significant.

Figure 4. Portions of three light curves of the white dwarf HL Tau 76. Each point is a 5-second average of the brightness of the star. Abscissa marks occur every 200 seconds.

Figure 5. Power spectra of two light curves of the white dwarf g29-38. Major peaks and some of the peaks identified as harmonics or linear combinations of the major peaks are indicated.

Figure 6. Short section of light curve of DQ Herculis showing the 71-second oscillations. Each point is a 7-second integration.

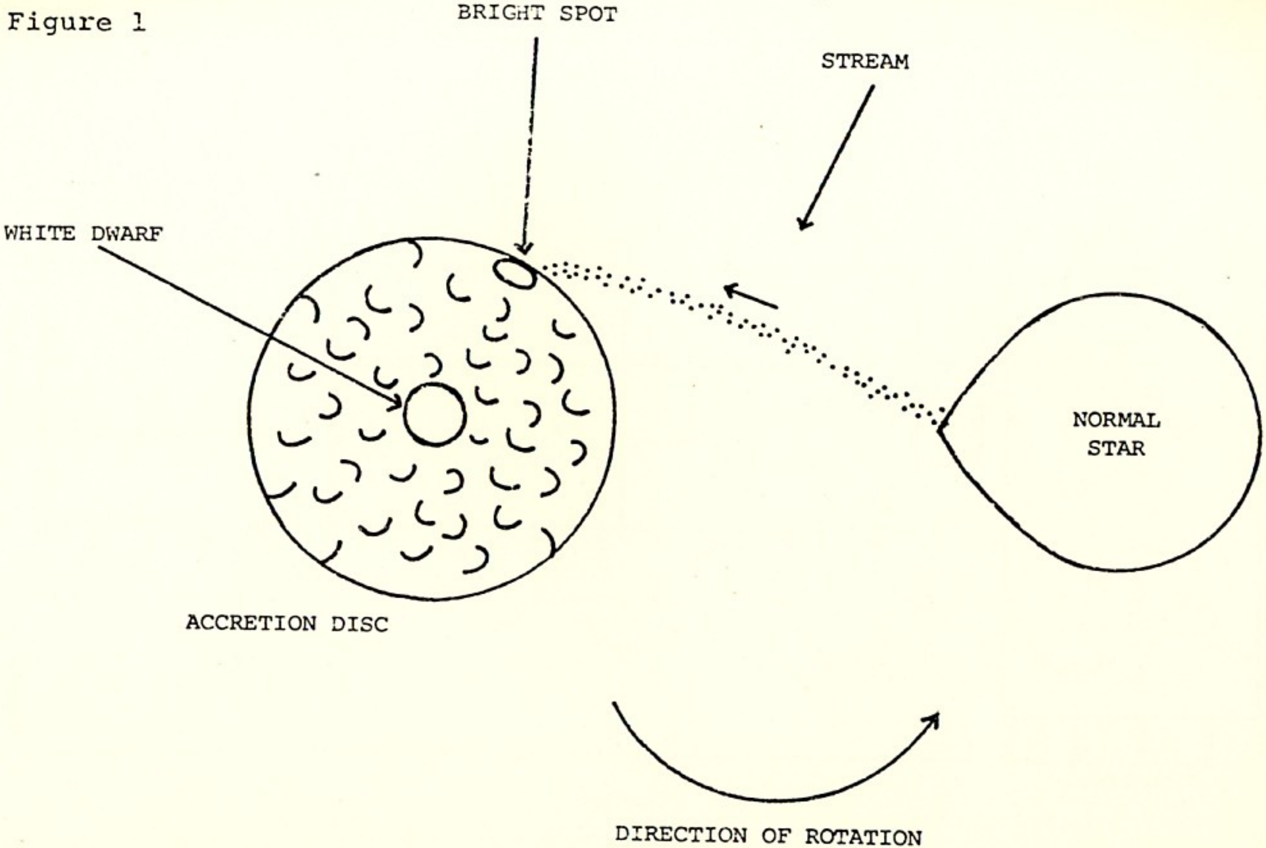
Figure 7. Phase shift and amplitude of the 71-second oscillations in DQ Herculis. Orbital phase is the fraction around the double star orbit; zero corresponds to mid eclipse when the two stars are in line towards us.

Figure 8. Eclipse light curve of UX UMa. Also shown are the amplitude and phase of the 30-second oscillations in the light curve.

Figure 9. Power spectra of succesive sections of the light curve of dwarf nova CN Orionis during the rise to maximum. The power spectrum of the first section of the light curve is plotted at the bottom; successive sections, showing the gradual drift to smaller periods, are plotted above each other.

Figure 10. Main optical pulse of the Crab pulsar. Each point represents the total accumulation of photons in a 20-usec integration.

Figure 1


BRIGHT SPOT
STREAM
WHITE DWARF
NORMAL STAR
ACCRETION DISC
DIRECTION OF ROTATION

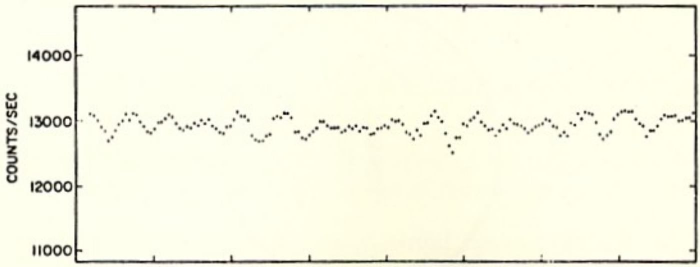


Figure 2

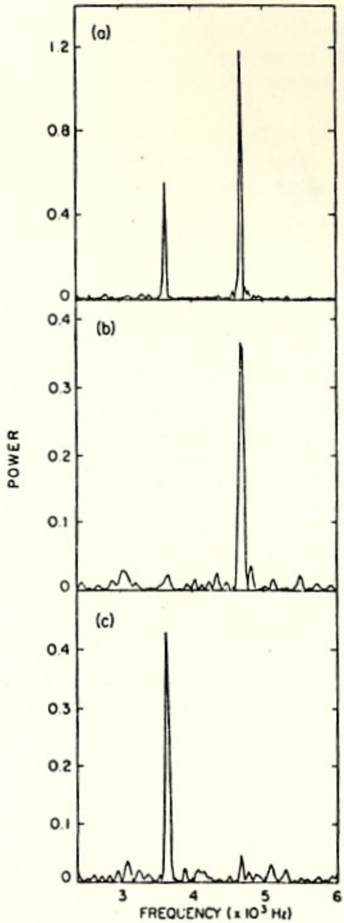
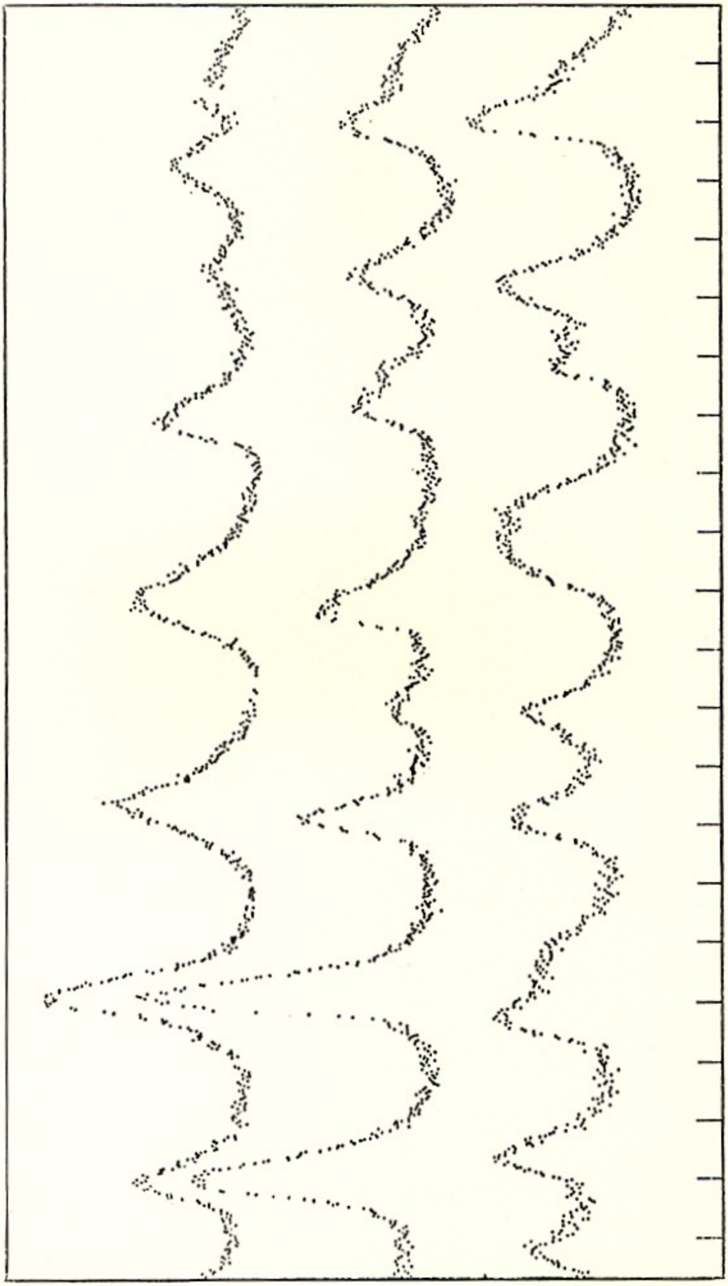


Figure 3



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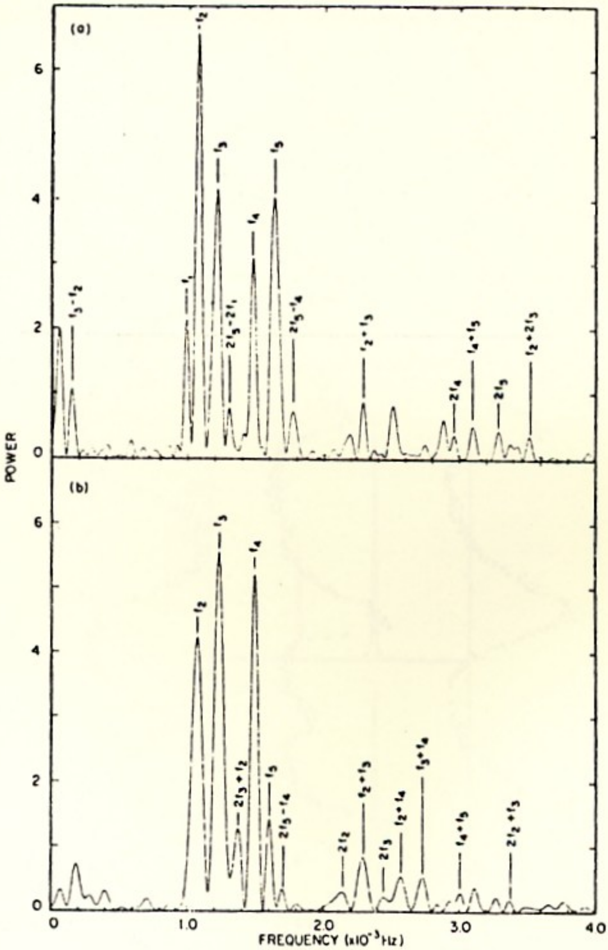

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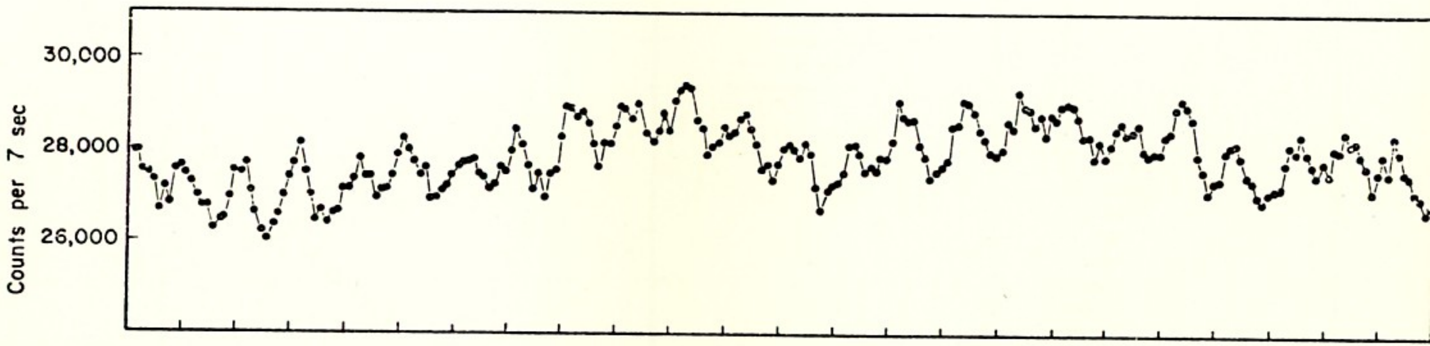

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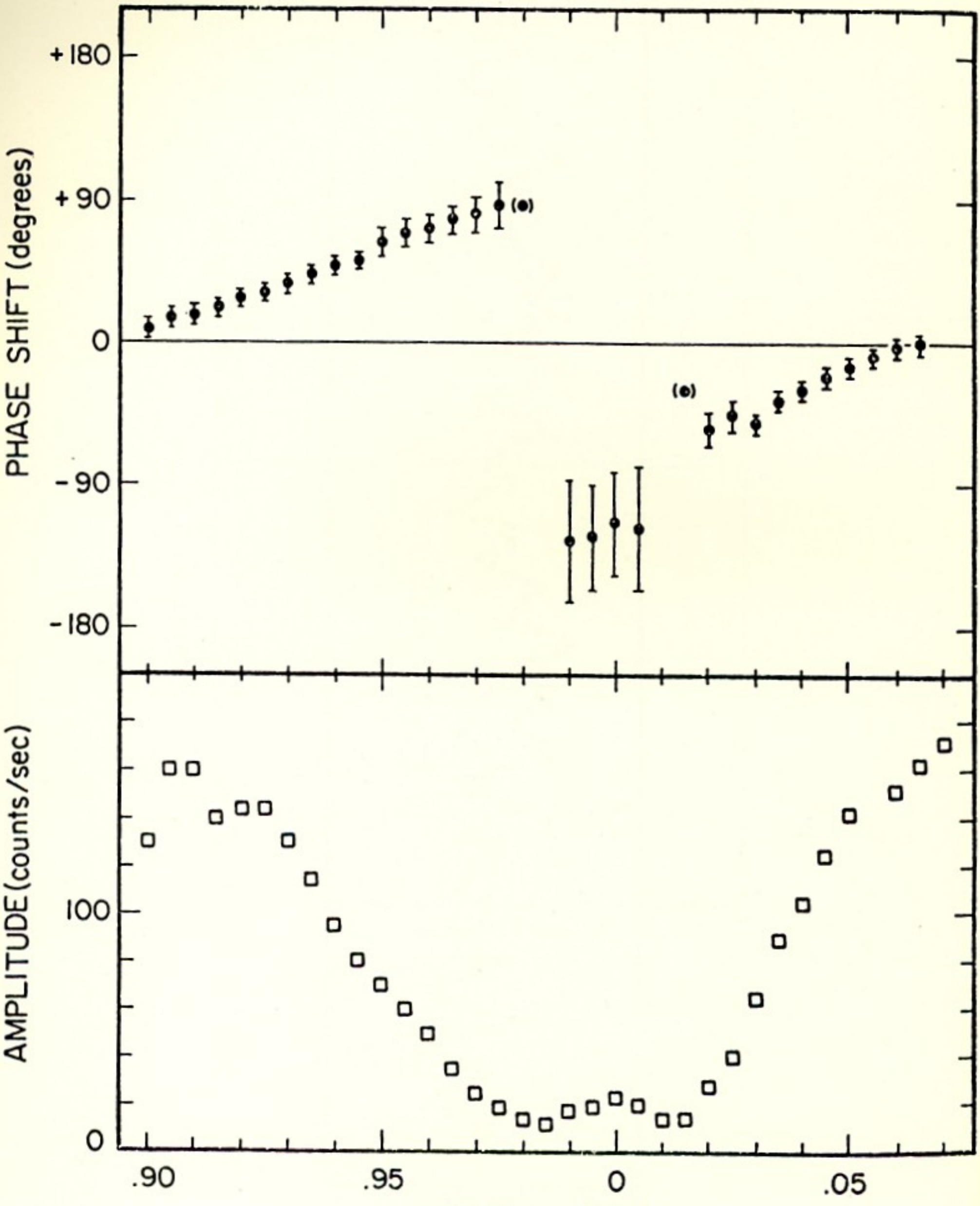
+180
+90
0
-90
-180
PHASE SHIFT (degrees)
(•)
(•)
100
0
AMPLITUDE (counts/sec)
.90
.95
0
.05
ORBITAL PHASE
Figure 7

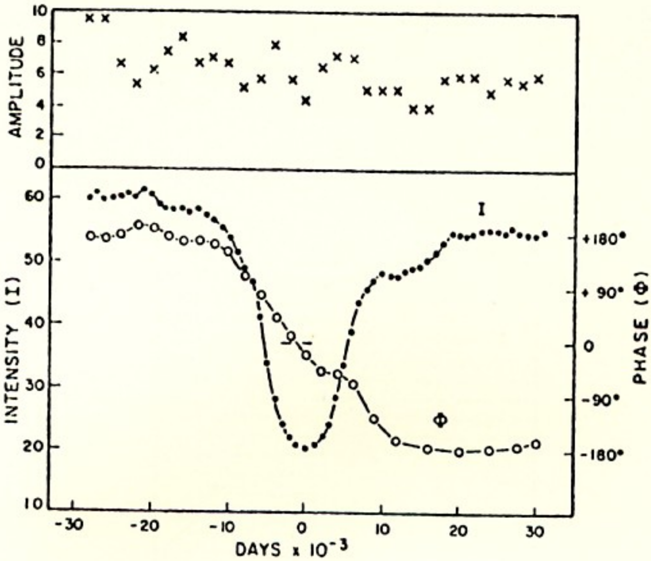
AMPLITUDE
10
8
6
4
2
0
INTENSITY (I)
60
50
40
30
20
10
I
Φ
+180°
+90°
0
-90°
-180°
PHASE (Φ)
-30
-20
-10
0
10
20
30
DAYS x 10⁻³

Figure 8

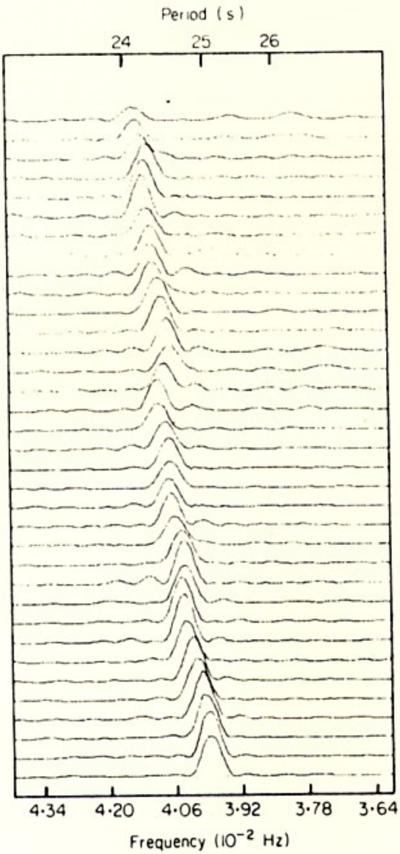

Figure 9

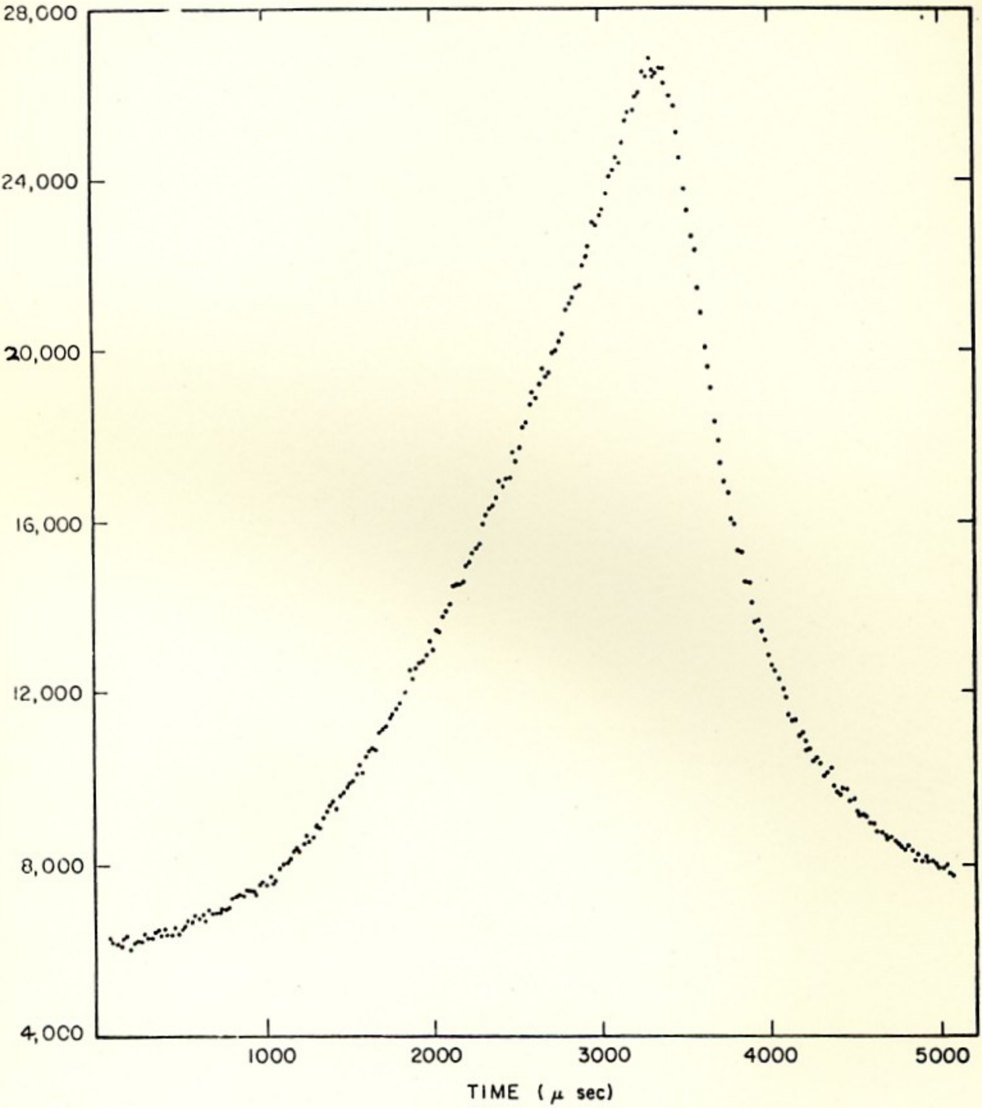
28,000
24,000
20,000
16,000
12,000
8,000
4,000
1000
2000
3000
4000
5000
TIME (μ sec)

Figure 10