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NOTES FOR THE OBSERVER

by T. P. Prabhu

1. Gamma-ray astronomy

Most of our current knowledge on the large-scale structure of the universe has been acquired through photons. The constraints imposed by biological evolution have limited our direct perception to only one octave of the almost infinite frequency spectrum of photons. While the recent developments in detector technology are enabling us to record all the spectral regions transmitted through earth's atmosphere, the exploitation of artificial satellites has added to our knowledge by opening up the vistas of new frequencies not observable from the ground-based observatories. Observing the universe in the light of γ-rays has been one such recent achievements of astronomy. These photons of the highest energy (from 0.1 MeV to beyond 100 GeV) that travel unimpeded through the interstellar and intergalactic medium only to be fully absorbed by the earth's atmosphere can now be studied from spacecrafts.

The importance of γ-rays in astronomy was realized through theoretical studies more than three decades ago. E. Feenberg & H. Primakoff (1948 : *Phys. Rev.* **73**, 449) showed that the scattering of starlight photons off the high-energy cosmic-ray electrons leads to γ-ray production. S. Hayakawa (1952 : *Prog. Theor. Phys.* **8**, 571) studied the interaction of cosmic-ray nuclei with diffuse matter in space and concluded that the π^0-mesons produced in these interactions would decay into γ-rays. In the same year, G. W. Hutchinson (1952: *Phil. Mag.* **43**, 847) investigated the bremsstrahlung radiation of cosmic-ray electrons and found that whereas the magnetic bremsstrahlung occurs at radio frequencies, the collision bremsstrahlung has the energies of γ-rays. The knowledge of these three major processes of γ-ray production, and the speculation on the possible sites where matter and antimatter annihilate to produce these rays induced the first attempts to detect them from celestial sources.

The earliest experiments (1949–1952) using balloons and V-2 rockets could only set upper limits on the cosmic γ-ray flux. The first positive detection of low-energy γ-rays had to await the moon-probe Ranger 3 (J. R. Arnold *et al.* 1962: *J. Geophys. Res.* **67**, 4876) and of high-energy γ-rays the third Orbiting Solar Observatory (W.L. Kraushaar *et al.* 1972: *Ap. J.* **177**, 341). In the meantime, yet another branch of astronomy was born: R. Giacconi and his collaborators (1962: *Phys. Rev. Lett.* **9**, 439) pioneered the observations of cosmic x-rays The x-ray astronomers had the advantage that the sources were brighter in this spectral region than at higher energies. The discovery of an increasing number of x-ray sources and also the diffuse background, in turn, provided clues to the γ-ray astronomers as to where exactly they should look for sources of their interest. The sensitivity and resolutions of the γ-ray telescopes were considerably improved in the second Small Astronomy Satellite (SAS-2) in

1972 and in the Cosmic-Ray Satellite (COS-B) in 1975. Subsequent years have also witnessed an improvement in the balloon-borne telescopes. Furthermore, the very high-energy γ-rays ($E > 10^{11}$ eV) can be observed even from ground through the detection of Cerenkov radiation produced when these photons pass through the earth's atmosphere. The reflectors at Narrabri, Australia (constructed originally as optical intensity interferometer), at Mount Hopkins, U.S.A., and the multiple mirror array at Ootacamund have pioneered in this area.

We have now accumulated sufficient information on the appearance of the universe through this spectral window, to sit and ponder over and to plan observations with a new generation of equipments and telescopes in the forthcoming years. C. E. Fichtel & J. I. Trombka (1981) have compiled all the available information in their book *Gamma Ray Astrophysics* (NASA SP-453). A prolonged meeting held to discuss 'galactic astrophysics and gamma-ray astronomy' during the eighteenth general assembly of IAU, Patras, has now been published (*Sp. Sci. Rev.* **36**, 1–335, 1983). Considerable time was devoted to γ-ray astronomy during the eighteenth international cosmic-ray symposium held in Bangalore in 1983. A very good review on the galactic γ-ray sources has also appeared recently (F. Bignami & W. Hermsen 1983 : *A. Rev. Astr. Ap.* **21,** 67).

The most important mechanisms of γ-ray emission in celestial sources involve the interaction of energetic particles with matter or the magnetic/photon field. The cosmic-rays, active galactic nuclei, compact objects like pulsars, and explosive events like supernovae are naturally the most important sources of γ-rays. In addition, the interaction with the particle flux from the sun and also the natural radioactivity can cause observable amount of γ-ray emission from the solar system objects. Space probes have taken advantage of these effects—as also the effect of cosmic-ray interactions—to study the surface composition of planets and their satellites by the technique of remote sensing in the γ-rays. The proximity of sun renders it observable even at these high frequencies. The energetic particles released through solar flares interact with matter and field to produce γ-rays. The forthcoming period of solar maximum will witness tremendous improvement in the study of solar flares in this energy range.

The γ-ray emission in the Galaxy may be classified into diffuse and compact components. The diffuse γ-ray emission originates in the diffuse interstellar medium and is enhanced around massive clouds. Since the dominant process for the origin of diffuse γ-rays is the interaction of cosmic rays with the diffuse matter, the luminosity depends only on the cosmic-ray density and the matter density. Furthermore, the galaxy is 'optically thin' to γ-rays. Thus, one can now aim at a selfconsistent model of the matter density distribution in the Galaxy as also the distribution of cosmic rays. The solution to one of the nagging problems in this field—the choice between galactic or metagalactic origin of cosmic rays in the Galaxy—now appears in sight.

The COS-B satellite discovered 25 localized γ-ray sources. The available angular resolution was too poor to determine which of these are of stellar dimensions. Rotating magnetic neutron stars in the form of pulsars, or accreting neutron stars (and blackholes) such as in binary x-ray sources are the most promising candidates for compact γ-ray sources. However, only four of the 25 known compact galactic sources have been unambigously identified; three of these are pulsars: PSR 0833 — 45 (Vela), PSR 0531+21 (Crab) and PSR 1747 — 46; the fourth one is the binary x-ray source Cygnus X-3. Young supernovae are also likely candidates for compact γ-ray sources and indeed several such objects may be hidden from us behind large quantities of interstellar dust or deep inside the massive molecular clouds. Very high energy γ-rays have been observed by the telescopes at Ootacamund and elsewhere from the Vela and Crab pulsars and also from Cygnus X-3.

While the sensitivity of the present-day γ-ray telescopes is insufficient to record diffuse or compact sources in distant galaxies, γ-ray emission has already been detected from several active galaxies. These include the Seyfert galaxy NGC 4151, the radio source Centaurus A (NGC 5128) and the quasar 3C273. Though it may take some time before we can observe the normal galaxies in γ-rays, the Magellanic Clouds will be within one's reach with the next generation of telescopes. The data on these objects will not only improve our understanding of the relationship between the distribution of matter and of γ-rays, but also would throw more light on the problems of the origin and distribution of cosmic rays (*cf.* V. L. Ginzburg & V. S. Ptuskin 1984: *J. Ap. Astr.* **5**, 99).

We witness in the radio galaxies an ejection of energetic particles from the nucleus to the two radio lobes. Thus one would naturally expect these nuclei to be bright in γ-rays. Probably the energetic events in different types of active nuclei are of similar origin, the currently favoured model being accretion onto a supermassive blackhole. So far, only the nearest radio galaxy Cen A, and the bright Seyfert NGC 4151 have been detected in this spectral region. On the other hand, the brightest quasar 3C273 as also a few of the fainter ones (2S 0241 + 622 and 2251 — 179) have been detected. One may note that the quasar 2S 0241 + 622 has the lowest known redshift, and is hence presumably the nearest one. No γ-rays have been detected from BL Lacertae objects, though several of these have been detected in x-rays. Their reduced γ-ray output may be understood in the light of other evidences for the lack of diffuse matter in them—such as the low strength of spectral lines—emission as well as absorption.

A large number of active nuclei may be detected during the next decade. At present, one can only record their excess cumulative flux in terms of the diffuse γ-ray radiation at high galactic latitudes, over the expected flux of galactic origin. This diffuse radiation may also have significant contribution from the matter-antimatter annihilation. The baryon-symmetric big-bang cosmology proposes a scenario for the latter possibility. In this picture, the matter and antimatter were initially created in equal proportions. While most of the matter and antimatter annihilated, the local excesses of matter or antimatter were amplified to form superclusters of matter and antimatter. The annihilation continues even at the present epoch at the boundaries of such superclusters. More detailed observations of the diffuse background, particularly the observations of its anisotropy, will help in testing such a model.

An unsolved puzzle of γ-ray astronomy concerns the burst sources. One may classify the burst sources into two categories : (i) the low-energy bursts which are being continually observed during the last decade, but not yet theoretically explained, and (ii) the hard γ-ray bursts expected to accompany the evaporation of primordial blackholes, but not yet observed. The low-energy (< 100 keV) bursts last a few seconds to tens of seconds. None of the observed bursts could yet be identified with a known celestial object, though suggestions have been made that a burst observed on 1979 March 5 may be associated with the supernova remnant N49 in the Large Magellanic Cloud.

The evaporation of a primordial blackhole of 10^{15} gm would result in a burst of 100 MeV γ-rays lasting about 10^{-7} s. The lack of observed bursts of such characteristics may be used to set upper limits to the space density of such primordial blackholes.

We may recapitulate that the science of γ-ray astronomy is only a little over two decades old. While the period 1962–1972 may be termed the decade of discoveries, the following ten years have given us a glimpse of the universe in the light of γ-rays. We now have some idea as to which objects are seen well in this spectral region. We also have some knowledge on the spectral energy distributions of a few sources. We may now plan to observe such and similar other possible sources in continuum as well as in emission lines (*cf.* R. Ramaty & R. E. Lingenfelter 1983: *Sp. Sci. Rev.* **36**, 305) with more sensitive telescopes of the forthcoming decade. The implications of such efforts would be far-reaching in terms of an enhanced understanding of the physical processes operating in diverse astrophysical objects as well as on the origin and structure of the universe itself.

2. Elliptical galaxies: shape and luminosity distribution

Edwin Hubble wrote in 1936 (*The Realm of the Nebulae*, p. 39 of the 1958 Dover edn): 'Elliptical nebulae are highly concentrated and show no indication of resolution into stars. The luminosity falls rapidly away from bright, semistellar nuclei to undefined boundaries. As far as exposures have been pushed, diameters, and hence total luminosities increase steadily with increasing exposure-time. Small patches of obscuring material are occasionally silhouetted against the luminous background, but otherwise these nebulae present no structural details.' Obviously, the elliptical galaxies are not a pick of the celestial beauties. Yet their simplicity of structure —an assemblage of stars with hardly any gas and dust—lured the theorists into modelling them as a one-parameter family. Further observations have, however, revealed more baffling aspects of their personality, and the efforts have been on the increase during the recent years to gather more data and attempt to explain them.

When Hubble wrote the paragraph quoted above, the only parameters of ellipticals that could be studied quantitatively were the projected axial ratios and the intensity distribution. Measurements requiring higher observational complexity were undertaken during the following decades. The first of these was the photoelectric measurement of integrated colours. The spectroscopic measurements of the strengths of absorption lines, and also of their widths which lead to an estimation of stellar velocity dispersions, became feasible a little later. Finally, detailed spectroscopic observations with a view to determining the rotation of ellipticals became possible only a decade ago.

Early observations of the colours, line-strengths and velocity dispersions all showed a correlation with the intrinsic luminosities, which led one to believe that the ellipticals belong to a one-parameter family, with their properties determined only by their mass. An improvement in the accuracy of measurement now reveals a large spread in all such correlations, which fact, together with several peculiarities seen in the systems individually or collectively, undermines one's hopes in a simple explanation. Furthermore, one now recognizes several classes of elliptical and diffuse spheroidal galaxies, as also the I0 galaxies which might be ellipticals which have recently acquired a copious supply of gas. All these galaxies should find place within a considerably enlarged family of elliptical galaxies and hence the scope of the problem is tremendously widened.

Axial ratios

At a given brightness level the apparent shape of an elliptical galaxy is close to an ellipse, as the name implies. One can measure the apparent axial ratio, but this quantity gives no clue to the three-dimensional shape of the galaxy. It appeared at first glance that all galaxies have an axis of symmetry coinciding with the axis of rotation. Hence Hubble (1926: *Ap. J.* **64**, 321) assumed that the ellipticals are oblate spheroids oriented randomly with respect to the plane of the sky. The apparent axial ratio q would then relate to the intrinsic axial ratio q_0 by the relation

$$(1 - q^2) = (1 - q_0^2) \sin^2 i,$$

where i is the angle between the shorter axis of the galaxy and the line of sight. The number of galaxies with intrinsic axial ratio q_0 that appear with a projected axial ratio between q and $q + dq$ will then be proportional to the value of d (cos i). If the distribution of intrinsic axial ratio is $f(q_0)$, it can be shown that the observed frequency of galaxies with apparent axial ratios between q_1 and q_2 is

$$N(q_1, q_2) = \int_0^1 f(q_0)\,(1 - q_0^2)^{-1/2}\,[(q_2^2 - q_0^2)^{1/2} - (q_1^2 - q_0^2)^{1/2}]\,dq_0.$$

Using the observed values N, the above equation may be numerically solved to obtain $f(q_0)$. Since Hubble's pioneering work, more effort has gone into deriving $f(q_0)$ and the work of A. Sandage, K. C. Freeman & N. R. Stokes (1970: *Ap. J.* **160**, 831) has served as a standard reference.

Recent observations show that the ellipticals do not rotate fast enough for the rotation to affect their shapes significantly. Thus, their shape is dictated largely by the 'pressure' due to the random velocities of individual stars. In such an event, one cannot, *a priori*, demand that they have an axis of rotational symmetry. B. Binggeli (1980: *Astr. Ap.* **82**, 289) and J. Binney & G. de Vaucouleurs (1981: *M. N. R. A. S.* **194**, 679) have attempted to model $f(q_0)$ under different assumptions of intrinsic shapes. While the oblate and prolate models give a most probable shape of $q_0 \simeq 0.36$, it appears that if the ellipticals are truly triaxial systems, we can infer nothing—even statistically—about their intrinsic axial ratios.

Furthermore, the axial ratios of ellipticals do not appear to depend on their luminosities. The observed frequency distribution is similar over a wide range—from dwarf to giant ellipticals. It is only recently that some indications have become available on the differences in the axial ratios in different samples. For example, it is likely that the double radio sources are associated with rounder ellipticals (T. P.

Prabhu & R. K. Kochhar 1984 : *Ap. Sp. Sci.* in the press). Also, the galaxies at the extreme ends of the luminosity range—the supergiant cD galaxies and the sub-dwarf compact and diffuse ellipticals—may have different distribution of axial ratios. The cD galaxies, in particular, appear to be flatter than normal ellipticals.

The intensity distribution

The surface brightness of elliptical galaxies falls monotonically, making it easier to fit the profiles. The surface brightness profiles are generally studied as major axis profiles and minor axis profiles, or as an 'equivalent profile' as a function of an equivalent radius defined as $r^* = (A/\pi)^{1/2}$. Here A is the area enclosed within an equal intensity contour. Surprisingly, an overwhelming majority of ellipticals can be described by a single profile-fitting function with one scale factor for surface brightness and another for radius. The two most popular functions are the Hubble law and the de Vaucouleurs law.

The law attributed to Hubble since he used it extensively was first used by J. H. Reynolds (1913 : *M. N. R. A. S.* **74**, 132) to described the central region of the Andromeda galaxy :

$$\frac{I}{I_0} = \frac{1}{(r/r_0 + 1)^2}$$

where I and r are the surface brightness and the radial distance. The parameter I_0 defines the central surface brightness, and r_0 the core radius. The law suggested by G. de Vaucouleurs (1948 : *Ann. d' Ap.* **11**, 247) is

$$\log (I/I_e) = -3.33\,[(r/r_e)^{1/4} - 1].$$

Here, r_e (the 'effective radius') is the radius inside which half the total light from the galaxy is emitted. I_e is the surface brightness at this radius. This law, often called $r^{1/4}$ law, has been widely used due to its linearity in a simple power of r. On a magnitude scale, it can be rewritten as $\mu = Ar^{1/4} - B$, where $\mu = -2.5 \log I$, $A = 8.33\ r_e^{-1/4}$ and $B = \mu_e - 8.33$. Thus μ_e and r_e can be evaluated just from a straightline fit as against the Hubble law where one has to try out different values of r_0. Furthermore, J. Kormendy (1977 : *Ap. J.* **218**, 333) shows that the two profile-fitting functions are empirically equivalent since they yield one set of scale parameters each : (I_0, r_0) or (I_e, r_e). By comparing these parameters derived for a sample of galaxies, Kormendy also shows that I_0 and I_e are correlated, and so are r_0 and r_e. Thus one may chose either function to fit the observed profiles.

A surprising relation obtained by Kormendy in the above mentioned work is, however, a relationship between the scale factors in surface brightness and radius. In blue light, he obtains

$$\mu_e = 3.28 \log r_e + 19.45 \text{ mag arcsec}^{-2},$$

with r_e expressed in kpc, measured along the major axis. This relationship implies that the surface brightness falls off more slowly in brighter galaxies. Translated into absolute magnitudes (M), this implies

$$M = -1.72 \log r_e + \text{constant}$$

and $M = -0.53\mu_e + \text{constant}.$

Even the supergiant cD galaxies to conform well to this relationship. In addition to the implications such a relation has on the formation of ellipticals, it is also a promising candidate for a distance indicator. B. Thomsen & S. Frandsen (1983 : *Astr. J.* **88**, 789) confirm that such a relation holds good for ellipticals in several distant clusters. They suggest using the relation as a cosmological test. Furthermore, the scatter in the relationship may point to the effects of projection. Certainly, this is an area where more work needs to be done.

Yet another method of profile-fitting is due to J. L. Sérsic and his colleagues at Cordoba (*cf.* Sérsic 1982 : *Extragalactic Astronomy*, Reidel, Chapter 2). The profile here is defined in terms of an area $A(\mu)$ enclosed by the equal intensity contour of surface brightness μ in magnitudes. The profile is described by the relationship in its most general form,

$$A = K(\mu - \mu_0)^N.$$

Considering the fact that A can be expressed as πr_*^2 , the value of $N = 8$ yields the $r^{1/4}$ law. The method may have some advantage when an additional parameter is needed to describe the luminosity distribution. J. L. Sérsic & V. M. Arreguine (1983: *J. Ap. Astr.* **4**, 225) show that, assuming $N = 8$ for ellipticals seen face-on, a departure from this value would result due to projection effects. Thus a statistical analysis of N as a function of the apparent axial ratio q may provide a clue to the three-dimensional structure of ellipticals. The observed intensity distribution has been used also by D. W. Olson & G. de Vaucouleurs (1981 : *Ap. J.* **249**, 68) among others to probe into the intrinsic shape of ellipticals. These authors find that oblate shapes are more favoured!

In addition to the Cordoba system, there have been other attempts to fit the observed profiles with functions incorporating an additional parameter. Particularly, if the outer region of an elliptical is affected by tidal interaction with a neighbouring galaxy, the semiempirical profiles due to Ivan King (1966 : *Astr. J.* **71**, 64) are useful. These profiles were originally derived for the globular clusters which are truncated due to tidal interaction with the Galaxy. The two scale parameters in radius are the 'core radius' and the 'tidal radius'. However, the interacting ellipticals are tidally distended rather than truncated and the better fit obtained with King models is only due to an additional parameter introduced (Kormendy 1977). Apart from the tidally interacting galaxies, the outer regions of cD galaxies also depart from a simple law of surface brightness. These latter galaxies have extended low-surface brightness envelopes, whose origin is debatable at present. The surface brightness profiles of ellipticals are similar over a large range in intrinsic luminosity of galaxies. However, there is some departure at extreme luminosity ends of the sequence. At the brighter end, we have the cD galaxies which are by far the most massive galaxies in the universe. First identified two decades ago (T. A. Mathews, W. W. Morgan & M. Schmidt 1964 : *Ap. J.* **140**, 35), these galaxies are characterized by envelopes which may extend to several Mpc in diameter. The surface brightness profile can be described well by such an envelope added to the $r^{1/4}$ law. These galaxies are generally the brightest in rich clusters. The suggestion by J. P. Ostriker & S. Tremaine (1975 : *Ap. J.* (*Lett.*) **202**, L113) that the cD galaxies might form by the merging of smaller galaxies into a larger one brought these objects to the forefront of astrophysical news. The sensational words 'mergers' and 'galactic cannibalism' have now become commonplace. The true nature of cD galaxies may probably be understood only when the excitement is damped and one learns more on their kinsfolk—the cD-like galaxies in poor clusters (W. W. Morgan, S. Kayser & R. A. White 1975: *Ap. J.* **199,** 545) and the first-ranking members of clusters (E. M. Malumuth & R. P. Kirshner 1981: *Ap. J.* **251,** 508). In return, the cannibals may show us the path to the communities with more civilised food habits.

It is of importance to study the elliptical galaxies at the other end of luminosity too. Dwarf ellipticals like M32 and NGC 205 (the companions of Andromeda galaxy) have been studied for long, and several diffuse spheroidal galaxies are known in the local group since the first of their kin, the Sculptor system, was discovered by H. Shapley in 1937.

In a recent paper, A. Wirth & J. S. Gallagher (1984 : *Ap. J.* in the press) have studied a sample of dwarf ellipticals. By comparing the derivative of the luminosity profiles, Wirth & Gallagher identify two families of ellipticals: the classical dwarf ellipticals like M32 which are scaled-down versions of giant ellipticals, and the diffuse systems like NGC 205 which have lower surface brightness falling off nearly linearly with radius.

A discussion on brightness distribution in elliptical galaxies is incomplete without the mention of the isophote twists. If the density distribution in ellipticals were to vary uniformly such that the surface of constant volume emissivity are homologous ellipsoids, the equal surface-brightness contours (isophotes) of the projected image would be similar ellipses, with their axes well-aligned with each other. What one observes in practice in a large number of ellipticals is, however, different. The ellipticity as well as position angle of the major axes of the isophotes vary as one moves from the centre outwards. Though data have been accumulating over the years, beginning with the classic work of Martha Liller (1960: *Ap. J.* **132,** 306), it is only now that implications of the isophote twists for the structure of ellipticals are being realized. As many as half the ellipticals show some degree of isophote twisting. Often one finds the ellipticity increasing from centre outwards and the major axis rotating uniformly. But this is not a rule; there are several examples of a minimum or maximum ellipticity at an arbitrary radius, and even of abrupt changes in ellipticity and position angle.

A possible explanation of isophote twists is that the axial ratios of the equal-density ellipsoids vary from centre outwards. In such a situation, the inclination of the elliptical to the line of sight (*i.e.* the projection effects) can contrive to produce the observed changes even if the principal axes of all these ellipsoids are aligned in space. Under this assumption, the isophote twists suggest a means of guessing the inclination of ellipticals and hence estimating their three-dimensional shapes. L. Benacchio & G. Galletta (1980: *M. N. R. A. S.* **193,** 885) have made such an attempt. Yet, as always, better data for a larger sample are called for.

In summary, even the simplest observations of elliptical galaxies—their brightness distribution—indicates that they are not as simple as they once appeared. Yet one's confidence need not be shaken. These gas-poor, discless systems are certainly simpler than other types of galaxies. Once we solve the problems posed by their surface photometry, and also answer the questions raised by other observations, the path will be paved for a better understanding of even more complex, multi-component galaxies.

3. Spectra of classical Cepheids

The first detailed study of spectral features of a large number of Cepheids was made by O. Struve and A. D. Code during 1944–1947 which forms the basis of our present understanding of Cepheid spectra. It was extended by R. P. Kraft in the 1960s and a summary of the results derived from spectroscopic studies is given by Kraft (1967 : *I. A. U. Symp. No. 28*, p. 207).

Since the effective temperature of a Cepheid varies over its period, the spectral type also varies over its cycle. Normally, the variation of spectral type is in the range F1–G0, but it may extend up to K2 for long-period Cepheids like RS Puppis ($P = 44$ d). The variation of luminosity class is normally in the range II to Ib. At the phase corresponding to luminosity minimum, the spectrum of a Cepheid resembles closely that of a normal F or G supergiant. The spectrum contains numerous lines of ionized and neutral species of Fe, Cr, Ti, V, *etc.*, the hydrogen lines, and the H and K lines of ionized calcium. Figure 1 shows the spectrum of the brightest and nearest Cepheid α Ursae Minoris (Polaris) in the blue spectral region.

At the luminosity maximum the spectral type lies between F5 and F8 for Cepheids of all periods. However, at this phase the spectra show a number of peculiar features. The hydrogen lines become anomalously strong, the strength of Ti II and Fe II lines also increases. These abnormalities in Cepheid spectra are believed to be due to rapid movement of gaseous masses in the atmosphere at this phase.

For Cepheids with periods longer than four days a transient emission component is observed in Ca II lines at the phases shortly after the luminosity maximum. The

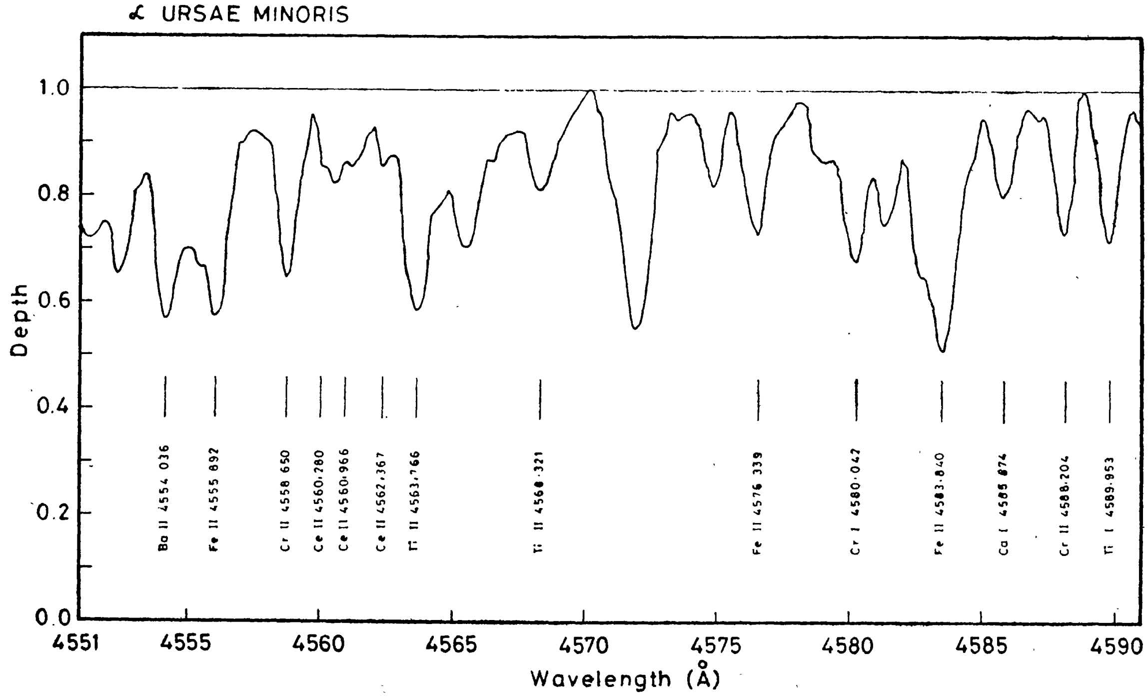

Figure 1, Spectrum of the Cepheid α Ursae Minoris in the blue region.

duration of this transient phenomenon increases with period but does not exceed 0.4 period. Though the strength of this emission component correlates with absolute magnitude, it does not follow the relationship derived by O. C. Wilson & M. K. V. Bappu (1957 : *Ap. J.* **125**, 661) for nonvariable supergiants.

Some of the Cepheids exhibit composite spectra. These confirmed and suspected binary Cepheids show systematically smaller light amplitude than a single Cepheid of similar period. The orbital periods lie between 3–30 yr. The long-period Cepheids RW Camelopardalis and KN Centauri have bright companions of earlier spectral types (T. L. Evans 1968: *M. N. R. A. S.* **141**, 109).

Radial Velocities

The Doppler shifts of absorption lines in the spectra of Cepheids give information on the radial velocity of the stellar atmosphere. The variability of observed radial velocity of Cepheids was first detected by A. A. Belopolskii in 1894 who wrongly ascribed it to the binary nature. Harlow Shapley who studied the radial velocity variation of a large number of Cepheids, pointed out in 1914 (*Ap. J.* **40**, 459) the untenability of the binary hypothesis. The observed irregularities in the shape and elements of the light curve, and the observed variation of temperature, could not be explained by a simple binary explanation. Moreover, Shapley demonstrated that the derived size of the orbit of secondary companion turns out to be smaller than the radius of the star itself.

The radial velocity data for a large number of Cepheids were published by A. H. Joy (1939 : *Ap. J.* **86**, 363) and D. W. Stibbs (1955: *M. N. R. A. S.* **115**, 363). The light and radial-velocity curves of Cepheids are closely related to each other. The minimum of radial velocity occurs very close to the time of maximum light; in other words, the velocity curve is a mirror image of the light curve. If the radial velocity curves are arranged in the order of increasing period, we get a sequence similar to the Herzsprung sequence of light curves. The asymmetry of velocity curve varies in the same way as the light curve and the discontinuity at the period of nine days is also present. It is caused by a double minimum in the velocity curve at this period. The amplitude of velocity variations is around 30–40 km s^{-1}. The amplitude correlates well with luminosity variation. P. P. Parenago (1954 : *Perem. Zvezdy* **10**, 193) found a relationship between these two amplitudes given by $A_v = (35.3 \pm 0.3)\ A_{pg}$ which holds good for a considerable range in periods.

If the radial velocity curve represents the motion of the stellar surface, then the phase relation between the light and velocity curves implies that the star is brightest when it is expanding through its equilibrium radius and not when its radius is smallest, as might have been expected intuitively. This observed retardation of maximum brightness behind minimum radius, or the phase lag, is usually in the range of 0.1 to 0.2 period. This observation proved to be a pain in the neck for all simple theories proposed to explain the variability of Cepheids.

Radii

An emperical method to determine the radius of a Cepheid using the radial velocity and photometric data was devised by Walter Baade in 1926 (*Astr. Nach.* **228**, 359) and improved by Wesselink in 1946 (*Bull. Astr. Inst. Netherlands* **10**, 91). The underlying assumption in the Baade-Wesselink method is that over the pulsation cycle of the Cepheids, there exists a functional relationship between the surface flux (*i.e.* the energy radiated per unit area) and the colour, measured by say $B-V$ index of the star. If the colour index $B-V$ is known as a function of period, then one can select pairs of phase with the same values of the $B-V$ index. With the above hypothesis, the surface brightness is also expected to be the same for the pair of phases of equal colour index. As a result, the magnitude difference for these two phases is a consequence of the difference in the size of the star at these phases. We can write for a pair of phases of equal colour

$$M_1 - M_2 = 2.5\,(\log R_1^2 - \log R_2^2) = 5 \log (R_1/R_2).$$

The displacement $R_1 - R_2$ can be determined by integrating the velocity curve between the times t_1 and t_2 corresponding to those phases. However, the observed radial velocity of the star is not the same as the actual velocity of the stellar surface relative to the centre of mass due to the projection effects and limb darking. A correction factor $p = 24/17$ is customarily used for converting the observed radial velocity to the true velocity. Knowing $R_1 - R_2$ and R_1/R_2 for different pairs of phases over the cycle, one can determine the function $R(t)$.

In order to apply this method, it is necessary to have very accurate photometric as well as radial velocity observations. The matching in phase of the light and colour curve with the radial velocity curve must be precise to about 1% of the period if an accuracy of 10% is to be obtained in the derived radius estimate.

L. A. Balona (1977 : *M. N. R. A. S.* **178**, 231) has developed a generalized version of the above method. In this method, instead of choosing a pair of phases of equal colour and using brightness differences and displacements at these phases, the principle of the maximum likelihood is employed to solve for a best line through all data points M_v, surface brightness F_v, and linear displacement ΔR.

Atmosphere abundances

Atmospheric abundances of various elements for several bright Cepheids have been derived by different workers using high-dispersion spectra. The abundances of iron group elements, Ti, V, Cr, Mn, Fe, Ni *etc.*, for the Cepheids in the solar neighbourhood do not differ significantly from the solar value. However, for distant Cepheids the observed Fe abundance shows a good correlation with the galactocentric distance. Since the observed Fe abundance of Cepheids reflects that of the interstellar medium, Cepheids have been used by many investigators to derive the radial abundance gradient in the disc of our Galaxy (*cf.* S. Giridhar 1983 : *J. Ap. Astr.* **4**, 75).

The abundances of carbon, nitrogen and oxygen for a large sample of Cepheids have been derived by R. E. Luck & D. L. Lambert (1981: *Ap. J.* **245**, 1038). Carbon and oxygen are considerably underabundant in the Cepheid atmospheres while nitrogen is enhanced. These changes in abundances are larger than those predicted by standard evolutionary calculations, and possibly indicate extensive mixing of the material processed by CN and ON cycles.

(*S. Giridhar*)

4. Spectrograph efficiency at higher dispersions

An astronomical spectrograph is designed keeping a number of factors in view (see R. S. Bingham 1979: *Quart. J. R. A. S.* **20**, 395). A well-designed spectrograph should have no light loss due to the overfilling of the grating and the camera. A particular spectrograph is designed for a specific wavelength region and dispersion. A deviation from these specifications will lead to a drop in efficiency. When a spectrograph designed for a lower dispersion is used with a finely ruled grating to obtain a higher dispersion, there is a drop in efficiency as shown below. The following results will help decide the useful limit to which a spectrograph can be pushed beyond its optimum dispersion.

We deal with the following parameters :

d = groove spacing,
α = angle of incidence measured from the grating normal (see figure 2),
β = angle of diffraction (positive when it is on the same side of the normal as α),
m = an integer specifying the order,
λ = wavelength of light,
f_{coll} = collimator focal length,
f_{cam} = camera focal length,
P = linear dispersion,
r = Bowen demagnification factor, arising from the fact that $\alpha \neq \beta$ for a finite λ [*cf.* equation (3) below],
R = reduction factor,
θ_B = blaze angle,
AB = major axis of incident beam,
A′B′ = major axis of diffracted beam,
σ = angle of deviation.

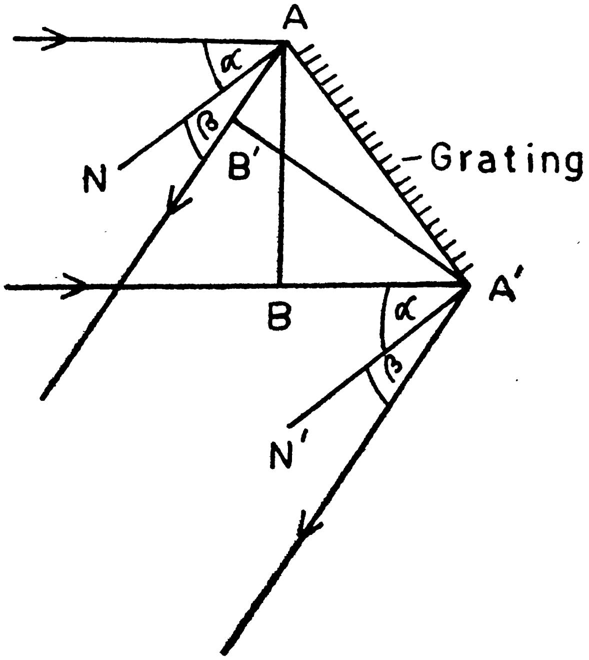

Figure 2. The geometry of diffraction.

The relevant equations are (*e.g.* D. R. Hollars & H. J. Reitsema 1974 : *Publ. Astr. Soc. Pacific* **86**, 330)

$$d(\sin\alpha + \sin\beta) = m\lambda, \qquad \ldots(1)$$

$$P = (F_{\mathrm{cam}} \times d\beta/d\lambda)^{-1}, \qquad \ldots(2)$$

$$r = \mathrm{d}\beta/\mathrm{d}\alpha = \cos\beta/\cos\alpha, \qquad \ldots(3)$$

$$R = (f_{\mathrm{cam}}/f_{\mathrm{coll}}) \times r, \qquad \ldots(4)$$

$$A'B'/AB = \cos\beta/\cos\alpha, \qquad \ldots(5)$$

$$\sigma = \alpha + \beta, \qquad \ldots(6)$$

$$\theta_B = (\alpha + \beta)/2, \qquad \ldots(7)$$

$$\sin\theta_B = m\lambda/2, \qquad \ldots(8)$$

$$\alpha = (\sigma + 2\theta_B)/2. \qquad \ldots(9)$$

Equation (2) shows that for a fixed focal length, P can be decreased (*i.e.*, a higher dispersion obtained) by increasing $\mathrm{d}\beta/\mathrm{d}\lambda$, by using a more finely ruled grating. Equation (8) shows that this will lead to an increase in θ_B (for a fixed m and λ). This implies that α will increase and β will decrease [*cf.* equation (9)]. This will have a three-fold effect:
(i) The major axis of the projected ellipse on the grating will increase since $AA' = AB \sec\alpha$; (ii) for increasing α and decreasing β equation (8) shows that the major axis of the diffracted beam increases; and (iii) the grating demagnifies more [equation (4)], implying that the slit can be opened more to obtain the same projected slit width. If the spectrograph is so designed that the projected ellipse just fills the grating and that the diffracted beam just fills the camera, an increase in α will not only overfill the grating, but will also overfill the camera; the combined loss due to this can more than offset the gain of light because of a wider slit; the loss can become particularly serious at high dispersions. Furthermore, there is no gain by opening the slit beyond the size of the seeing disc of the star.

In most cases the net loss is due mainly to the overfilling of the grating. The fractional loss at the grating can be approximately obtained from

$$l = (\sec\alpha - \sec\alpha_0)/\sec\alpha$$

where α_0 is the angle of incidence corresponding to the grating being just filled. The plot of l as a function of α for some values of α_0 (10, 25 and 40) is shown in figure 3. In the case of spectrographs at Cassegrain/coudé foci, the shadow of the secondary will occupy progressively larger area of the grating as α increases; consequently, the curves in the figure will rise even more steeply.

Another fact is brought to notice by this analysis regarding gratings and echelles: A smaller value of r [equation (4)] allow us to open the slit wider and consequently allows more light to pass through. For this to be achieved, α should be greater than β. We find from the Bausch & Lomb grating catalogue that only one echelle (56 mm × 126 mm) allows us to keep $\alpha > \beta$ (for $\tan\theta_B = 2$, $\sigma = 10°$), if we are just to fill the echelle. For all other echelles, either α should be less than β ($r > 1$), or the echelle should be underfilled which leads to an under-utilization of the ruled surface.

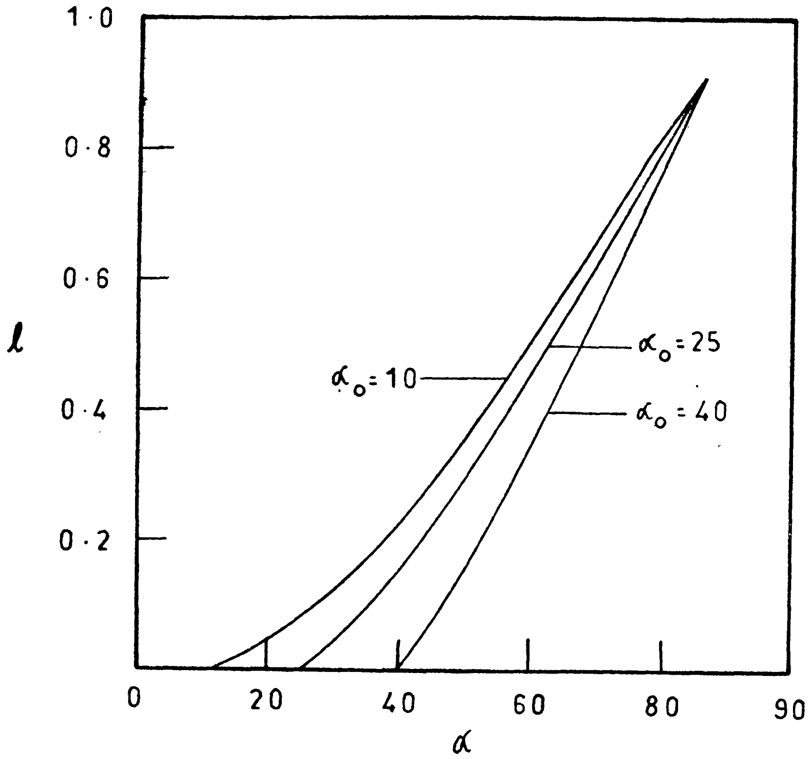

Figure 3. The fractional light loss l at the grating as a function of the angle of incidence α, for three values of α_0, the angle of incidence at which the beam just fills the grating.

Thus a spectrograph cannot remain efficient when higher dispersion is achieved simply by changing the grating. In most cases the loss occurs only at the grating and in some cases both at the grating and the camera. C. G. Wynne & S. P. Worswick (1983 : *Observatory* **103**, 12) have also recently considered the problem of light loss. They suggest the use of an anamorphic lens system, consisting of two cylindrical lenses, in front of the slit. With such a system the beam would have an elliptical cross-section with the minor axis lying in the direction of dispersion, thereby reducing the light loss both at the grating and the camera.

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