C. V. Raman's research in astronomy

Rajinder Singh

The celebration of 28 February as the National Science Day in India is due to the discovery of the Raman effect – the change in the wavelength of monochromatic light after it is scattered by a transparent medium. The effect was discovered on 28 February 1928 by C. V. Raman and K. S. Krishnan (see Figure 1). In 1930, Raman received the Physics Nobel Prize for his work on light scattering and the discovery of the effect named after him. He is known for his contributions in the fields of acoustics, optics and spectroscopy. Less known are Raman's activities in the field of astronomy.

While writing on the history of astronomy in the 20th century, some authors made passing remarks on C. V. Raman and the Astronomical Society of India (ASI)[1,2]. A number of biographies show various aspects of Raman's life, but none of them go into the details of his interest in astronomy. Also, the *Scientific Papers of C. V. Raman* (volumes I–VI), brought out by the Indian Academy of Sciences, Bangalore, do not mention Raman's work in astronomy.

Raman observed heavenly bodies such as Jupiter, Saturn and Mars. He presented his observations at the meetings of ASI (founded in 1910), and the results were published in the *Journal of the Astronomical Society of India* (*JASI*). The present article is based on the monthly/annual reports of ASI and Raman's publications in the journal. It gives a detailed review of Raman's astronomical research and his activities in the Society.

Raman and the Astronomical Society of India

In May 1910, the famous Halley's comet was observed in India. In Calcutta, this evoked a strong interest in astronomy. According to the first issue of *JASI*, a few gentlemen in Calcutta put up a proposal to form an astronomical society. The first meeting was called on 26 July 1910. H. G. Tomkins, an astronomer and an audit and accounts officer, was elected as Chair. In a meeting on 27 September 1910, a Council was elected and it was decided to register the society, which had 117 members on 26 August. Members of the society were supposed to meet once a month to present their observations and read papers. The first session began on 1 October 1910. The main objective of ASI was to foster interest in general and practical astronomy[3].

Raman enters

Raman's interest in astronomy can be traced back to his college days. He frequently visited the Madras Observatory[4] and had observed the lunar eclipse with a small telescope before he came in contact with ASI. On 27 February 1912, he was elected a member of ASI and in the meeting on 26 March, his election was confirmed. Just a year later, in February 1913, he became an Honorary Secretary of the Society. And a few months after that in June 1913, he was posted as Librarian and Secretary to the Scientific Sub-Committee. For the 1913–1914 session, he was appointed as Director of the Variable Star Section and Librarian. During 1920–21 he served as a member of the Council. Apart from these official duties, he gave a number of lectures as well.

Raman's lectures and papers in the *Journal of the Astronomical Society*

The diffraction of light and its relation to the performance of telescopes

In the monthly meeting on 28 May 1912, Raman stated that he would first discuss the fundamentals of the diffraction of light and then show its relevance to telescopic work. However, he largely followed on the lines laid down by Lord Rayleigh.

Raman observed that, according to textbooks, light rays after reflection from a paraboloid mirror condense on a point. From a practical astronomer's point of view, it is not so. In the case of a telescope, the entering beam of light is limited by a circular aperture; what we get at the focal plane of the telescope as the image of a point source is a diffraction pattern which consists of a central bright disc followed by successive dark and bright circular rings of greatly reduced intensity. In actual astronomical work, the second and third bright rings cannot ordinarily be seen as they are too faint.

Raman explained the formation of the diffraction pattern of light in the case of

Figure 1. K. S. Krishnan, the German physicist Arnold Sommerfeld and C. V. Raman at the Indian Association for the Cultivation of Science (IACS) – 1928 (Courtesy: Raman Research Institute, Bangalore).

a narrow rectangular slit which is placed at a large distance from a light source. He showed that the central bright band can be calculated by

$$\sin \theta = \lambda / a,$$

where λ is the wavelength and a the width of the slit.

Then he showed that in the case of a circular slit, diffraction rings are produced. The position of the first dark ring is given by

$$\sin \theta = 1.22\lambda / d,$$

where d is the diameter of the slit.

Now, what do these diffraction patterns have to do with telescopic work? He said:

> 'If, . . . , the image of a mathematical point is not itself a point but a diffraction pattern, it is evident that the telescopic image cannot be an exact representation of the object viewed. Much detail is necessarily obliterated. The simplest case is that of a double star. A photograph of the diffraction pattern due to two adjacent point sources as seen through a circular aperture is shown in fig. 4 (see Figure 2) in the plate. It is seen that the two discs have run together into a slightly elongated patch and, except probably under the most favourable atmospheric conditions, it would be impossible to detect that an object of this kind was a double star, or a triple star or one star, by itself.'

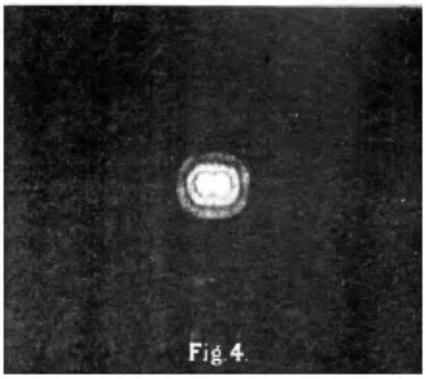

Figure 2. A photograph of the diffraction pattern due to two adjacent point sources as seen through a circular aperture (IIA Archive).

And further,

> 'Here lies the principal advantage of telescopes of large aperture. As the angular diameter of the diffraction disc due to a point source decreases in inverse proportion to the aperture, the resolving power increases "pari passu" (means hand-in-hand) provided that the figuring of the mirror or lenses continues perfect. The same principle applies also in planetary work. Other things being the same, the larger the aperture the finer the detail that can be revealed by the instrument[5].'

The above equation for a circular slit is based on the assumption that the screen on which the rings are observed is at a large distance from the slit. In order to reduce the distance, the simple solution is to put a lens just behind the aperture to focus the diffraction bands. Raman proceeded to show its application to astronomy and affirmed that 'we may regard the object-glass or refractor of a telescope as serving this purpose and the angular diameter of the rings seen in the focal plane would be determined by precisely the same formulae'. Taking the Society's reflecting telescope, which had an aperture of 4″ and yellow light of wavelength about 1/50,000″, he calculated the angular radius of the 1st ring as 1.2″.

In the above cases, the source of light must be perpendicular to the slit. Raman wrote that '. . . it is also possible for the incident beam of light to be restricted in width by an obliquely-held aperture and such cases are fairly common in spectroscopic work'. He showed that under these conditions, the diffraction pattern becomes unsymmetrical, the bands on one side of the system become much broader than on the other side (see Figure 3). It is worth mentioning that already in 1906, while he was at the Presidency College, Madras, Raman had given the 'mathematical law of obliquity' for a rectangular aperture[6].

Raman's lecture was illustrated with a number of diagrams and lantern slides. The President of the Society remarked:

> 'Anybody who is used to Telescopes must be accustomed to the diffraction rings round the stars. In a perfect telescope there will be seen a star which looks like a pearl and round it one or two diffraction rings. *I have never heard the explanation before of the intensity of the rings* (emphasis added).'[7]

Not only the theoretical explanation, but also the quality of Raman's slides were highly appreciated by the President.

Astronomical optics

On 25 June 1912, Raman delivered a lecture entitled 'Astronomical optics' that dealt with the application of the interference of light in astronomical research[8]. He demonstrated, with a simple experiment, the observation of the bright and dark fringes due to interference. He instructed the audience to take an undeveloped photographic plate and draw two lines very close to each other with a needle; keep the plate close to the eye and parallel to the source of light, like the filament of an ordinary electric lamp or the edge of the flat flame of a paraffin lamp from a distance and observe the interference pattern. He suggested a repeat of the experiment with a greater dis-

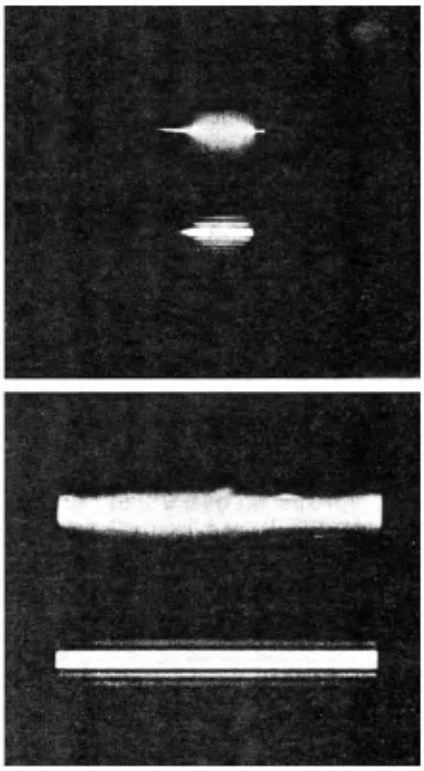

Figure 3. Unsymmetrical diffraction pattern due to obliquity, that is, if the source of light is not perpendicular to the slit (IIA Archive).

tance between the lines, and asked them to note the pattern. With this experiment, Raman showed that the width of the fringes is inversely proportional to the distance between the two slits. However, if the experiment was performed in such a way that 'if, instead of observing the narrow edge of the flame through the pair of slits, the flame is viewed broadside on, the interference fringes will be found to be no longer visible'. The reason for this is that each of the different parts of the source produces its own set of interference fringes. What does this mean for telescopic observations? Raman stated:

> 'If the object-glass of a telescope had a cover put on with two narrow parallel slits cut in it at some distance a part from each other and a bright star were observed through the telescope, we would see in the field of view a narrow strip of light crossed by fine interference fringes. If, instead of a star, a planet were observed, the interference fringes would probably be no longer visible, the cause of their disappearance being the superposition of the interference fringes due to the different parts of the source. It is evident that the extent of the confusion depends on the angular diameter of the object viewed, and on the angular width of the interference fringes in the field. If the slits on the cover of the object-glass were gradually drawn apart, the fringes would gradually decrease in width and at a certain stage would become obliterated. The distance apart of the slits at which the first fringes cease to be visible gives us a measure of the size of the object viewed.'

And further,

> 'If, instead of being a disc of finite size, the object was a double star, the change in the visibility of the fringes as the distance between the slits is increased can be very readily calculated. If the angular separation of the double star (say θ) were equal to $\lambda/2a$ (λ being the wavelength and a the distance between the slits), it is clear that the bright bands in the fringes due to one of the stars in the double would coincide with the dark bands of the other set, and the fringes would have just disappeared. When a, the distance between the slits is further increased, so that $\theta = \lambda/a$ the fringes would re-appear with practically their full original intensity since the bright bands of one set coincide with the bright bands of the other set and *not* the dark bands. In fact as a is gradually increased the fringes pass through alternative cycles of visibility and invisibility. With a disc of finite size instead of a double star as the object, the interference fringes do not regain their full degree of visibility when a is increased beyond the value at which they first disappeared. There should, however, be a very appreciable re-appearance.'

Raman tried to observe the effect, that is, the restoration of the fringes after their initial disappearance in the laboratory. But he had no instrument at his disposal with which he could change the distance between the two slits. However, he found a simple solution and suggested that the same effect can be seen if the size of the light sources was gradually increased.

Spectroscopic notes

Raman's next paper 'Spectroscopic notes' started with a comment on a paper published in the *Bulletin of the Kodaikanal Observatory* (1909, **16**). In that paper, Gilbert Walker outlined a theoretical study on the curvature of the lines in the spectrum formed by a plane grating. Raman pointed out that the phenomenon was of practical importance in designing a spectroheliograph – an instrument used to capture the photographic image of the sun at a single wavelength. He gave a shorter and general equation

$$a(\sin \phi_n/{-}\sin \phi) = n\lambda \operatorname{cosec} \theta \quad \text{(eventually } a(\sin \phi_n + \sin\phi) = n\lambda \operatorname{cosec} \theta), \qquad (1)$$

where a is the grating interval, λ the wavelength, and the polar co-ordinates (θ, ϕ) indicate the direction of propagation of the diffracted waves. The formula reduces to the ordinary formula used in spectroscopic work when $\theta = \pi/2$. It can be used to calculate the form of the lines in the spectrum formed by linear sources of any length and curvature. Ramen derived an expression for calculating the radius of curvature of the lines 'when the source is a short straight narrow slit parallel to the lines of the grating as in spectrometric work, and the spectrum of the nth order is photographed with a camera of focal length f on a plate held at a particular angle with the diffraction rays'.

In the experimental part of the paper, Raman wrote that 'by using a fairly long slit parallel to the rulings on the grating as the source of light, the curvature of the lines even in the 1st order spectrum can readily be observed and photographed, and measurements can then be made on the plates to test the application of Walker's formula and of the general eq. (1) given above'[9]. Raman also reported that in one of the discussions, he had ventured to suggest that it might be possible to get a photograph of the spectrum of a meteor with suitable arrangements. Acting on the advise of the President, Raman found that such a photograph had been taken at the Harvard College Observatory.

Saturn in a small telescope

In Bankura, Raman had observed Saturn with the 5″ Cooke telescope and wrote:

> '. . . not only was the crape ring an easy object, but for nearly one hour while the definition was perfect, I made out Encke's marking in the A ring and held it steadily for practically the whole period. Encke's division [gap in the A ring], . . . , is regarded as a difficult object which even a 10″ refractor often fails to discover. The conditions for observing it are, however, at present very favourable.'[10]

He said that some time ago, he had viewed Saturn with a refractor of a little less than 3″ aperture and made out Cassini's division (the region between the rings A and B). Since his return from Bankura, he had been working (in Calcutta) on Saturn with the 7″ Merz refractor, and was able to reconfirm his observation of Encke's division. Besides that, he observed two markings in the B ring. They were very faint and seemed to indicate some kind of definite structure in the B ring.

On 31 March 1914, Raman reminded the readers that in one of the previous meetings he had mentioned that Cassini's division could be observed even with a

3″ telescope. Some of the members expressed their doubt on whether such a performance was even theoretically possible with that aperture. Raman proceeded to defend his statement: 'If the object-glass of a telescope is covered by a rectangular aperture, and a point-source of light such as a star is viewed through it, the principal part of the image seen in the field consists of a small rectangular area of light, the angular distance of the dark margin from the center is seconds of arc being given by the formula: $(\lambda/a) * (180 * 3600''/\pi)$. Taking $\lambda = 1/50,000$ of an inch for yellow light and the aperture $a = 2.87''$, the angle is found to be 1.4 seconds of arc.'

Raman applied the above formula to the observation of double stars as follows: 'If a double star whose angular separation is 1.4 seconds is seen through the instrument, there would be a distant falling off in illumination between the positions of the geometrical images which might enable the object to be distinguished from a single star under suitable conditions.'

He stated that the falling off in illumination would be more easily appreciated if instead of two point sources, two fine linear sources were close together and parallel to the edges of the aperture. 'Experiment shows that resolution is quite possible at an angular separation of the two sources equal to that given by the above formula, the illumination in the center of the field being about 1/5th less than on either side of it, if the two lines sources are of equal intensity. If the angular separation is double of this, i.e. 2.8″, the field would show absolutely black line separating the two components.'[11] In the case of two illuminating surfaces separated by a dark line of division, such as the rings of a planet, the conditions for the resolution are far more favourable.

> 'If the source consisted of two equally illuminated surfaces separated by a dark gap of 4″, the telescopic field of 2.87″ glass would still show the division very dark. With a dark gap of 0.5″ [which is equal to Cassini's division] the illumination in the center of the field would still be 50 per cent less than on either side of it and this should be capable of being observed with ease.'

Raman applied the above theory to the actual case of Saturn's rings as observed on 16 February 1914. He obtained the following data from the *Nautical Almanac:*

	Major axis	Minor axis
A ring	5.7″	2.5″
Cassini's division	1.0″	0.5″
B ring	9.3″	4.1″

He stated that from these figures and the above discussion, it was evident that a 2.87″ telescope would be capable of showing Cassini's division right round the ring at the present epoch. 'A steady instrument and a comfortable position for the head and eyes of the observer should be sufficient to enable any of our members to verify this by an evening observation in the quiet of their homes.' He said that by stopping down the telescope, he could get glimpses of Cassini's division even with 2″ aperture; the difference in the brightness of the A and the B rings was very evident with such a small aperture.

On the diffraction phenomena observed in the testing of optical surfaces

Raman's last lecture/article was not published in detail, but only as an abstract. It dealt with the diffraction phenomena on surfaces. Lord Rayleigh had observed that when light from a point source is focused by a reflecting surface and the cone of light converging to the focus is partially or wholly cut off by a sharp straight edge, the appearance of the surface when studied with the aid of the reflected light (partly or almost entirely cut off) indicates the degree of the optical perfection of the surface. When the surface is optically perfect and the edge cuts off the cone of rays converging to the focus, the reflecting surface appears dark as a whole but the two edges of the surface on either side remain very bright. Rayleigh explained that the residual luminosity of the edges of the surface is due to the diffraction of light. Light reflected by the surface, instead of converging to a single point, forms a diffraction pattern at the focus. The edges introduced into the focal plane do not entirely cut off the diffraction pattern, and the residual luminosity appears to come from the edges of the surface.

Raman showed that when the edge is put slightly in front of or behind the focal plane and placed so as to cut off the geometrical cone of rays, the residual luminosity of the two edges of the surface is unequal. The difference is probably due to the fact that the diffraction pattern at the focus is different from that formed in planes lying behind or in front of the focus[12].

Raman's observation of heavenly bodies

Eclipse of the moon

In 1913 at the Indian Association for the Cultivation of Science (IACS), a small observatory housing a 7″ Merz refracting equatorial telescope was constructed (Figures 4 and 5). With this telescope, Raman observed not only planets but also eclipses. He gave a short report to ASI on the observation of a lunar eclipse from the roof of IACS. He said: 'We had a fairly large party. . .We saw nothing till about 6-35 and then suddenly a narrow streak of light shone out. Beyond the uneclipsed portion, only a slight extension of the limb was visible. This apparent denseness of the shadow was probably due to the haze that covered up the horizon.'[13] He added: 'I saw the last total eclipse of the moon at Nagpur when the moon was quite low down near the horizon, but the surface of the moon was quite clearly visible. This I think was due to the dryness of the air at Nagpur.' Most probably Raman was talking about the lunar eclipse of the year 1910, which he observed at Nagpur with his 3″ refractor.

Figure 4. IACS observatory (Courtesy: IACS).

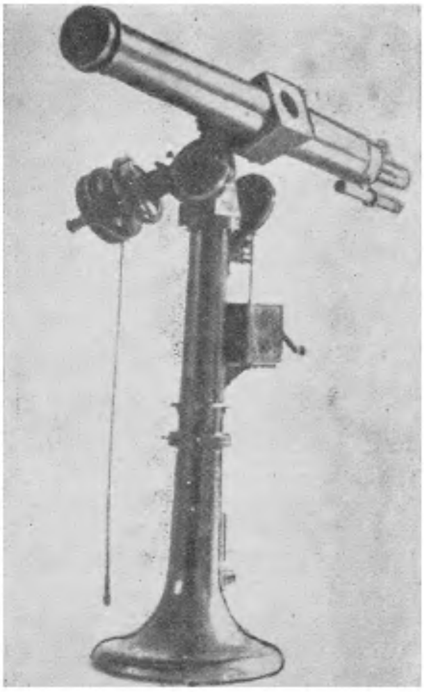

Figure 5. A seven-inch Merz refracting equatorial telescope (Courtesy: IACS).

Observation of the zodiacal light and the Gegenschein

The zodiacal light is caused by sunlight scattered by space dust in the zodiacal belt. It is a faint whitish glow seen in the night sky, which appears to extend up from the vicinity of the sun along the zodiac or ecliptic. It is so dim that light pollution renders it invisible. On very dark nights, it can be observed. There is also a very weak, but still slightly increased, oval glow directly opposite to the sun which is known as the Gegenschein. It is sunlight reflected by interplanetary dust. This is invisible in the presence of moonlight or light pollution or if it falls in the vicinity of the Milky Way. Raman observed these phenomena during 9–12 November 1913 in Bankura. He said that he saw the zodiacal band of light, which stretched almost right up to the zenith. It was possible to observe this as there were no street lights anywhere that could light up the sky. He wrote: '. . .in the constellation of Aries, a faintly luminous area of fairly small dimensions. . .which was clearest at a very early hour and gradually became more and more difficult to see till at last it merged into the luminosity of the horizon.'[14] Raman noted the position of this area in the constellation and from *Klein's atlas I*, he subsequently found the approximate position. Also, from the *Nautical almanac I*, he located the position of the sun on 10 November. He saw that it was opposite the bright area which he had observed. From that he concluded that what he saw was the Gegenschein. The area of light was some distance away from the Milky Way and quite dissociated from it. From the description on the Milky Way given in *Herschel's Outlines of Astronomy*, he decided that this particular region of the sky was no extension of the Milky Way which could have been mistaken for the Gegenschein.

With these observations, he concluded that it was possible to observe the phenomenon in India. He noted: 'However this may be, there is no doubt that for us in India, we have in the zodiacal light and allied phenomena, a splendid field for serious work by amateur astronomers who are situated away from the smoke and glare of the Calcutta sky. . .' Raman also mentioned that even in the midst of Calcutta, he had often viewed the zodiacal light before dawn (in the early morning hours) while looking for comets.

Study of Jupiter

According to the Annual Report of the IACS, Raman made a thorough study of the planet Jupiter for the year 1913. He made *a series of nearly 100 careful drawings of the surface of the planet* as viewed through the telescope during July–November 1913 (emphasis added). A string of remarkable features and progressive changes on the disc of the planet were noted by him. In the Report, it was promised to bring out a special bulletin of the Association with the drawings and observations. Unfortunately, Raman's work was lost forever as the bulletin was never published. Also, the annual reports of the IACS did not publish these drawings. One of the reasons seems to be that Raman's research on musical instruments took a central position. So, the special bulletin was on this research rather than on astronomy.

In the monthly meeting of ASI on 24 June 1913, Raman said that on the previous night he had observed Jupiter and all four satellites on one side of it. In November 1913, he observed the planet with a 5″ Cooke refractor. He stated: 'Incidentally I may mention that Jupiter has shown very remarkable features during this year. The great red spot was in conjunction with the south tropical disturbance, and its drift. . . . At the edge of the North Equatorial band and inside the Equatorial zone we have had a series of remarkable oval arch-like structures.'[15] He continued these observations at IACS with a 7″ Merz refractor.

In the 1920s, Raman focused on the molecular scattering of light. So far as his contact with ASI was concerned, for the years 1919–1920 and 1920–1921, he was elected as one of the members of the Council. But his scientific activities found their end. In the late 1930s, when he was asked what he would do if he lived his life again, Raman replied that he would like to become an astronomer. He also disclosed that in the 1920s, he left the field as he could not afford a proper telescope (*The Illustrated Weekly of India*, 23 April 1939). For Raman, astronomy meant not only the observation of stars, but much more. He informed a journalist that 30 years ago, he told Mahatma Gandhi that the growing discoveries in the science of astronomy and physics seemed to be a revelation of God and that science offered the best opportunity for a complete fellowship (*The Deccan Herald*, 21 December 1966).

Raman's work on astronomy did not bring him international fame as was the case in acoustics and the scattering of light. However, it helped him to establish contacts with influential British scientists in India who nominated him for the Fellowship of the Royal Society of London.

Raman's scientific work, social contacts and the Fellowship of the Royal Society of London

Gilbert Walker (Director General of Observatories) and J. Evershed (Director) of the Kodaikanal Observatory were two influential persons with whom Raman established close contacts during his work at ASI. It is evident from certain statements that Raman was proposed for an international expedition. In the *Bulletin of the Kodaikanal Observatory* (**LXXII**, p. 45), while writing the 'Report of the Indian eclipse expedition to Wallal, West Australia' from 1922, the author J. Evershed stated: 'Professor Raman of Calcutta kindly promised to join the expedition and assist in the work as planned above.' However, this expedition took place without Raman due to financial reasons. Evershed reported: 'I was compelled to limit the personnel to three only, including myself and Mrs Evershed. Prof. Maclean of Wilson College, Bombay, kindly arranged to join us and assist in work, but was unfortunately prevented by illness from coming.'

The importance of Raman's work in ASI can be judged from the fact that he was nominated by Walker for the Fellowship of the Royal Society of London. Two more members of the ASI – Evershed and Burrard – supported the nomination. They were three out of seven proposers. According to the nomination certificate:

> 'Although trained entirely in India has made considerable additions to our knowledge of sound and light, having published about fifty memoirs. The chief are: "Experimental Investigations on the Maintenance of Vibrations"; "The Dynamical Theory of Bowed Strings"; "Vibrations of Bowed Strings and of Musical Instruments of the Violin Family"; "On Kaufmann's Theory of the Pianoforte Hammer"; "On the Photographic Study of Impact at Minimal Velocities"; "On Hertz's Theory of Impact"; "Photometric Measurement of the Obliquity Factor of Diffraction"; "The Curvature of Lines in Diffraction Spectra"; "Colours of the Striae in Mica"; "The Diffraction Figures due to an Elliptic Aperture"; "The Colours of Mixed Plates".'

As we see in the paragraph above, Raman's research in acoustics and optics stood at the centre. He was proposed for the fellowship in November 1921 and elected on 15 May 1924 (ref. 16).

Concluding remarks

Raman's interest in astronomy can be tracked to his student days at the Presidency College, Madras and the observation of astronomical phenomena like the lunar eclipse in 1910. He observed Mars, Venus and Saturn. Raman made a number of drawings which were presented on the occasion of various meetings of ASI and IACS. Unfortunately, these valuable documents are not to be found. Indian historians of science are being appealed to 'chase for' them, as they belong to India's cultural heritage.

Though Raman's fascination for astronomy was greater than in other fields. He left the field of astronomy as he could not afford to buy expensive modern telescopes. The choice of a research field for a scientist seems to be influenced by his financial condition.

Raman's contact with influential members of ASI led to his nomination for the Fellowship of the Royal Society of London. His election, in 1924, raised Raman's status among the scientific community although his astronomical research work did not gain international fame. His example shows that apart from the scientific work, the social contacts of a scientist are important to raise his or her status.

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ACKNOWLEDGEMENTS. I thank Prof. Helge Kragh (University of Aarhus, Denmark), and Ms Christina Birdie and P. Prabahar (Indian Institute of Astrophysics (IIA), Bangalore) for the copies of the *Journal of the Astronomical Society of India* and for making me aware of the Digital Library of India, which contains not only the journal but also other historical documents (http://www.new.dli.ernet.in/index.html.en; 29 July 2010). The newspaper-articles from which I have quoted were given to me by the library members (Dr Patil and Mrs Geetha) of the Raman Research Institute, Bangalore. I am grateful for the help I have got from the members of the two libraries. I also thank to the Archives of the Royal Society of London for C. V. Raman's nomination letter for the fellowship of the Society. Thanks are also due to Prof. Michael Komorek and members of the Research Group – Physics Education, History and Philosophy of Science for supporting my research, and Prof. Falk Riess (University of Oldenburg, Oldenburg) for his comments on the earlier version of this article. I am also grateful Prof. D. C. V. Mallik (IIA, Bangalore) for valuable comments and suggestions. Without his help, the article would not have been in its present form.

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Edited and published by P. Balaram, Current Science Association, Bangalore 560 080.
Typeset by WINTECS Typesetters (Ph: 2332 7311), Bangalore 560 021 and Printed at Printek Printers, Bangalore (Ph: 2328 7763)