A Celebration of Colour in Astronomy

David Malin
Anglo-Australian Observatory.

Part I – Historical Background

INTRODUCTION

The extensive and rapidly-growing scientific literature on human vision is ample evidence that this is an active field of research. The response of the visual system under almost every conceivable circumstance has been examined. Unfortunately, very little seems to have been written about the response of the eye to the curious imaging conditions found in visual astronomy, probably because it is not nowadays an important part of astronomical research. But since our species first looked at the night sky and wondered about it, the eye was the only astronomical detector, and it remained so, long after the invention of the telescope increased its light-gathering power almost 400 years ago.

Photography had largely displaced the eye from the end of the telescope by the turn of this century. With its ability to integrate feeble light for long periods, the photographic plate has provided a scientific basis for an understanding of what the eye can see, and much else that it cannot. However, photography did nothing at first to compensate for the eye's poor colour response at low light levels, and no one was surprised or disappointed that from the beginning astronomical pictures were monochrome.

This was not the case with 'everyday' photography. When Daguerre's invention became a practical way to record the pattern of light in 1839, the inventor's case for a pension for donating his invention to the world was presented to both houses of the French parliament. The petition for the Chamber of Deputies was prepared by François Arago, while in the upper house Joseph Gay-Lussac performed the task. The distinguished astronomer Arago said nothing of the monochromatic nature of the Daguerrotype, but in his speech, the equally distinguished chemist Gay Lussac several times lamented its failure to record colours. He said[1]

> Let us hasten, however, to remark, without intending in any way to belittle the merits of this beautiful discovery, that the palette of this painter is not very rich in colors; black and white alone comprise it. The image with its natural and varied colors will, for a long time, perhaps for ever, remain a challenge to human ingenuity. . . . we must not overlook the fact that [with the Daguerrotype]

> colored objects are not reproduced in their natural colors. Here is . . . nature herself imposing her limitations on the new invention.

While nature's limitations of photography were eventually overcome to allow the representation of natural colours, to the considerable enrichment of our lives, astronomers have always been restricted by the eye's insensitivity to colour when the light levels are low. Thus, their ready acceptance of mere black and white in the pictures they are used to studying can come as no surprise, and has contributed to an indifference to perceived colour as an aid to astronomical understanding. That is not to say that astronomers are unaware of the importance of colour in their science; far from it. But the visualization of the colours that are implicit in their data is not normally considered useful or even necessary.

In this paper I hope to show that lack of colour sensitivity has hampered astronomical understanding since serious astronomical research began, a point I have arbitrarily chosen to coincide with the century that embraces the work of the pioneer astronomer William Herschel and the pioneer spectroscopist William Huggins. This paper selectively examines some of the historical evidence for this, especially with respect to observing non-stellar objects.

However, perhaps even more important to astronomy than the study of extended objects was the photographic discovery that most of the naked eye stars are much bluer than the sun and are now known to be representative of a young population. I will show how such colours can now be demonstrated photographically in a simple and direct way. Finally, we reproduce a large number of colour photographs made with the telescopes of the Anglo-Australian Observatory to demonstrate that the extra dimension of colour provides new insights to aid astronomical understanding. Like so many hidden aspects of nature revealed by photography, the pictures are informative as well as aesthetically pleasing.

THE PERCEPTION OF COLOUR IN ASTRONOMY

The drawings and descriptions of the early astronomers are full of interest and surprises for modern observers, especially for objects beyond the solar system. They provide a view of the night sky which is largely un-contaminated by modern preconceptions of what might be happening, and with little knowledge of the distance and physical nature of what was seen. These records of an earlier age also tell us a good deal about how the visual system functions when pushed to its limit. But what these early observers hardly ever discuss are the colours of the objects in the sky. We can only conclude that the colours that we can now easily demonstrate to be present was not visible to these diligent searchers of the skies.

We now know that the measurement of colour is an important part of the science of astronomy, but the realisation that such measurements were possible did not come about until after photography and spectroscopy were seriously applied to the science in the last third of the 19th century. Even then, the colour was not in any sense revealed, it was more an abstract realisation that some stars are bluer than the sun, some redder, that some nebulae had strong emission lines, others did not. Few imagined a colour photograph of the sky which showed the colour differences, and even if they did, it was never suggested that such a picture could be informative.

The colour of the world around us adds immeasurably to our enjoyment and understanding of it. However, it seems unlikely that colour vision evolved for that purpose, especially since an awareness of colour is evident in some of the simplest forms of life. More likely the perception of colour confers evolutionary advantages, at its simplest and most obvious, in the selection of food.

As the setting sun heralds the lower light levels of the night-time, human colour vision undergoes a series of subtle changes and the relative prominence of colours across the visible spectrum changes markedly. A qualitative description of this by Raman has been drawn to my attention by Ramaseshan (private communication). Raman had an extraordinary sense of the innate importance of colour in many branches of science, and he devoted the latter years of his life to understanding colour phenomena. He describes an experiment in a dark room where the visible spectrum produced from a tungsten lamp is projected onto a screen, and then dimmed in several stages in such a way that the quality of the light is not changed.

The extremes of the visible spectrum are quickly lost as its light level is lowered. Raman[2] notes '. . . the spectrum . . . exhibits a visible contraction at its red end. . . . A particularly noteworthy feature is that the blue part of the spectrum has visibly contracted.' As the light level is lowered further, this process continues. Yellow, at first the most conspicuous of the range of colours 'is still seen, but does not appear as more brilliant than the red and the green on its two sides. . . . the regions beyond the green now . . . exhibit only the dark blue and violet colours.'

At even lower levels of illumination, yellow disappears completely as a recognisable colour, but according to Raman, a feeble red remains and what appears to be the brightest part of the spectrum has shifted blue-wards from yellow to green. The disappearance of yellow indicates that the cones, the colour sensitive cells of the retina whose aggregate colour sensitivity peaks in the yellow-green part of the spectrum, are no longer fully active. Vision is now dominated by the rods, which have no colour discrimination. But if that is so, one wonders why red and green are still visible.

Carried to its conclusion, one might expect that his experiment would reach a stage where all colour would have vanished, leaving an almost imperceptible colourless glow where the blue-green part of the spectrum once was. This would correspond to the maximum sensitivity of the eye under the lowest conditions of illumination and the well-documented Purkinje effect[3]. At no time does Raman remark upon the complete disappearance of colour that would be expected under the conditions where light is barely visible *e.g.* Hunt[4]. Perhaps Raman's acute sensitivity to colour phenomena was because he had remarkably acute colour vision, even under very low light levels.

This seems to be confirmed by comments made by Raman and recorded by Ramaseshan[5].

> He [Raman] was familiar with the appearance of nebulae as viewed by a seven-inch telescope which was available to him in Calcutta – faint indistinct patches of light with no colour. During a visit to California [in 1924] he viewed the same objects through the 60-inch and 100-inch telescopes of Mt Wilson Observatory near Pasadena. He recounted vividly that the Ring nebula in Lyra exhibited flaming colours changing progressively from the external edge of its ring to its inner margin while the great nebula in Orion was a blazing area of variegated colour . . .

It is clear that Raman must have spent a substantial part of a night with access to telescopes, because the Orion and Ring nebulae are more than 180 degrees apart on the sky[5a]. This is the only account I know of where the colours of astronomical objects are so vividly described. Raman often said that he would have liked to have been an astronomer. If he really was equipped with the extraordinary colour vision suggested by the above comments he would certainly have revolutionised the subject.

THE COLOURS OF EXTENDED OBJECTS

An equally acute and questioning observer of nature was the astronomer William Herschel, who, almost 200 years earlier, in his long quest to understand 'The construction of the heavens' noted every aspect of the non-stellar objects, nebulae and galaxies, that so intrigued him. He spent much time surveying the star clouds of the Milky Way. 'On applying the [newly completed 20 foot] telescope to a part of the *via lactea*. I found that it completely resolved the whole whitish appearance into small stars. . .,[6]

It is interesting to speculate on the state of astronomy today if Herschel, or any of his successors with bigger and better telescopes, had noticed that the myriads of stars at the edges of the dark markings in the Milky Way were slightly fainter and yellower than those nearby, or that the dark lanes scattered across the Milky Way not only dimmed stars beyond, but changed their colour. If he had seen these effects, so well demonstrated in Figures 7 and 8, Herschel would probably have drawn the conclusion that much of the Milky Way was hidden from us by some semi-transparent medium that changes the colour of the stars as it dims them.

Given his fertile imagination, and a fondness for speculation, he may well have drawn a parallel between the dimming and reddening effect of the products of terrestrial combustion on sunlight with a similar process which he believed was occurring among the stars. Whatever he may have surmised about the energy source of the stars, he would have discovered the existence of interstellar absorption in 1800.

If he had also noted the vivid red and blue colours of the extended objects that appeared when he was 'on nebulous ground', it is impossible to know what he would have made of them. But it is probable that the association of bright blue stars with both dark patches and coloured nebulae would have been made very early. There also seems little doubt that the colour perception would have given a clear differentiation between nebulae and galaxies long before the 1900's, and the link between the 'zone of avoidance' in the Milky Way, and relationship to the dark bands crossing more distant spiral galaxies would have become obvious, or at the very least, the source of better-informed speculation.

But unfortunately, like the rest of us, Herschel and his successors had normal colour vision. However, some astronomical objects are bright enough to be on the threshold of colour vision. Hoskin[7] points out that William Herschel, as a most experienced observer, might be supposed to be aware of the relative colours of the brighter nebulae. This comment is in connection with his remarks on the nucleus of the Andromeda nebula (a galaxy, Messier 31) where he says 'The brightest part of it . . . begins to show a red colour . . .'. Herschel goes on to say that his sister Caroline had discovered a small nebula near it that 'is not the 32d of the *Connaissance des Temps* . . . (i.e. is not M32, but NGC 205). 'It shews the same faint colour with the great one (M31). . .[8]. Unfortunately, recent studies, of the nuclei of the M31 group of galaxies by Bica et *al.*[9] show that NGC 205 is actually much *bluer* than M31, though still a little redder than the sun. So colour is seen in some objects that we now know to be galaxies, and that are not especially coloured, but not in others of the same kind and brightness that Herschel examined with equal care.

Immediately after this, Herschel gives his famous description of planetary nebulae 'heavenly bodies, that from their singular appearance leave me almost in doubt where

FIGURE a. Probably the greatest naked eye observer of all time was William Herschel, seen here with a scroll commemorating his discovery of the 'Georgian' planet, later renamed Uranus. Despite his visual acuity and persistence, Herschel rarely reported seeing the colours of astronomical objects.

Foreword

David Malin of the Anglo Australian Observatory in Sydney, Australia was here with us a year ago on a visiting lecturer programme of the Third World Academy of Sciences. On that occasion he delivered a lecture at the Raman Research Institute under the auspices of the Indian Academy of Sciences, Bangalore. In this lecture he projected a selection of breath-taking colour photographs from the vast number that he has taken of the heavens and for which he is renowned. We felt that these magnificent pictures must be made available at a low cost to students and the lay public to bring home to them the aesthetics of science and to arouse in them an interest in astronomy. When approached, David Malin not only supported the idea enthusiastically of bringing out a special issue of *Current Science* but also sent us 60 exquisite colour photographs, some of which have never been published before. These, along with his lecture, are reproduced in this volume, **A Celebration of Colour in Astronomy.** We thank David Malin for his graciousness and generosity. Thanks are also due to members of the Raman Research Institute, Indian Academy of Sciences, Current Science Association and the Eastern Press for their unstinting help in bringing out this volume.

G. Srinivasan
S. Ramaseshan

> It will be reserved for time and precise observations to inform us if green or blue stars are not suns already in course of decay; if the different shades of those stars do not indicate a process of combustion in different stages ... it is probable, then, that upon this question of the colour of the stars, the part of observers may reduce itself, for a long time to come, to that of mere collectors of facts. The pleasure of connecting them with physical laws appears to be reserved for posterity.

Like Herschel, in the passage quoted above, Arago was referring specifically to the study of double stars. Among the isolated stars he found that blue ones were conspicuously absent:

> The existence of so great a number of blue and green stars in binary systems of stars, is a fact so much more worthy of attention, as I have remarked in the work cited above, [Arago's paper on the subject in *Connaissance des Temps* 1828] that among the sixty or eighty thousand isolated stars, the positions of which are to be found in the catalogues of astronomers, there are none, I think, inscribed with any other indications, in regard to colour, than white, red, and yellow. The physical conditions which determine the emission of blue and green light appear then to exist only in multiple stars.

There follows an inconclusive section entitled *Epoch of the discovery of blue stars* which briefly mentions the Australian astronomer Dunlop's 1827 Catalogue as describing a cluster of blueish stars. However, two pages earlier, the editors, in a footnote, warn '... that the results of [Dunlop] must be accepted with some degree of caution, since, in numerous instances, they have not been confirmed by subsequent observers'. A pity. Many star clusters are indeed dominated by blue stars.

Arago was incorrect in suggesting that bluish colours exist only in multiple systems. Today we know that most of the bright naked eye stars are in fact much bluer than the sun and that the colours of binary stars, while real enough, are accentuated by a contrast effect. Despite centuries of watching the sky, with and without telescopes, our ancestors never mention the existence of blue stars although white, yellow and red appear often. It seems that the blue-sensitive receptors in the eye are relatively few and far between and that the tiny images of stars fail to activate enough of them for us to see any stars as blue, except when they are associated with stars of a complementary colour. In addition, it must be admitted that even the bluest stars do not show saturated colours. This is unfortunate, since a knowledge that stars cover a wide range of hues would have strongly affected the way that early observers interpreted what they saw.

William Huggins, in his pioneering work on stellar spectral analysis was also led to speculate on the origins of star colours. In a section of a paper on the spectra of the fixed stars[13] he comments that 'it is highly probable that light when first emitted from the photosphere, or light-giving surface of the sun and of the stars, would in all cases be identical'. The colours, he believed, are produced by absorption of selected regions of what we would now call the underlying thermal continuum by the atmosphere of the star. He believed that this continuum was identical for all stars. He illustrates this with remarks about the absorption lines in the spectra of Betelgeuse and Aldebaran, which happen to be examples of red supergiants where an absorption mechanism *does* appreciably redden the colour of the star.

Like Arago, Huggins also considers that blue stars are only found in double stars and on examining the spectrum of the blue component of the binary Beta Cygni says that the star 'was remarkable for the faintness of the orange and yellow portions compared with the rest of the spectrum. The diminished brightness of these parts appears to be produced by several groups of closely set fine lines . . .'. This confirmed his view that star colours were produced by selective absorption lines from a continuum that was constant from star to star.

He had earlier noted the presence of a strong purple component in the image of the blue star of Beta Cygni when the telescope was put out of focus. This was almost certainly the ultraviolet light, which came to a different focus than the green light which appeared to surround it. However, Huggins did not recognise it as such and missed an important discovery. It is important to appreciate that neither Huggins nor his contemporaries saw red lines in their spectrographs, even when looking at objects rich in such lines, such as the Orion nebula[14,15]

THE ARRIVAL OF PHOTOGRAPHY

The lack of a detector sensitive to blue and ultraviolet light was rectified by the invention of photography by Daguerre in 1839. As mentioned above, the announcement of the discovery was made by Arago, who immediately encouraged the application of the new technique to astronomy. But the earliest plates were too slow to be useful and it was not until the mid 1870s and the invention of the dry gelatin emulsion that any real progress in stellar photography was made.

These early photographs provided the first completely objective way of measuring both the position and brightness of stars and it was soon noticed that stellar magnitudes derived from photographs were not the same as those obtained visually. One of the first to apply this observation to the determination of star colours was E. C. Pickering of Harvard College Observatory. In a series of articles on the development of astronomical photometry Weaver[16] says

> One of the earliest observers . . . to recognise the importance of photography as a means of determining the colors of the stars as well as their magnitudes was Pickering,[17] who stated: "The photograph furnishes an excellent test of the color of a star, since on comparison with the visual brightness, the stars which are faint photographically may be assumed to be red, and the bright ones blue . . ."

A more quantitative description and some of the first photographically determined colour indices of 'the fixed stars' were published a year later by Schaeberle[18]; however, nowhere is Schaeberle's paper is the connection between the photographic and visual magnitudes ascribed to a difference in colour.

By 1891, David Gill, then Her Majesty's Astronomer at the Cape of Good Hope and a leading advocate of photographic sky surveys had, with Jacobus Kapteyn of Leiden University, begun a photographic survey of the southern sky and was able to make the confident statement (Gill 1891):

> In comparing the existing eye estimates of magnitude by Dr. Gould [founder of the Cordoba Observatory in Argentina] with the photographic determination of these magnitudes, both Professor Kapteyn and myself have been greatly struck with a very considerable systematic discordance between the two. In the rich parts of the sky, that is in the Milky Way, the stars are systematically photographically brighter by comparison with the eye observations than they are in the

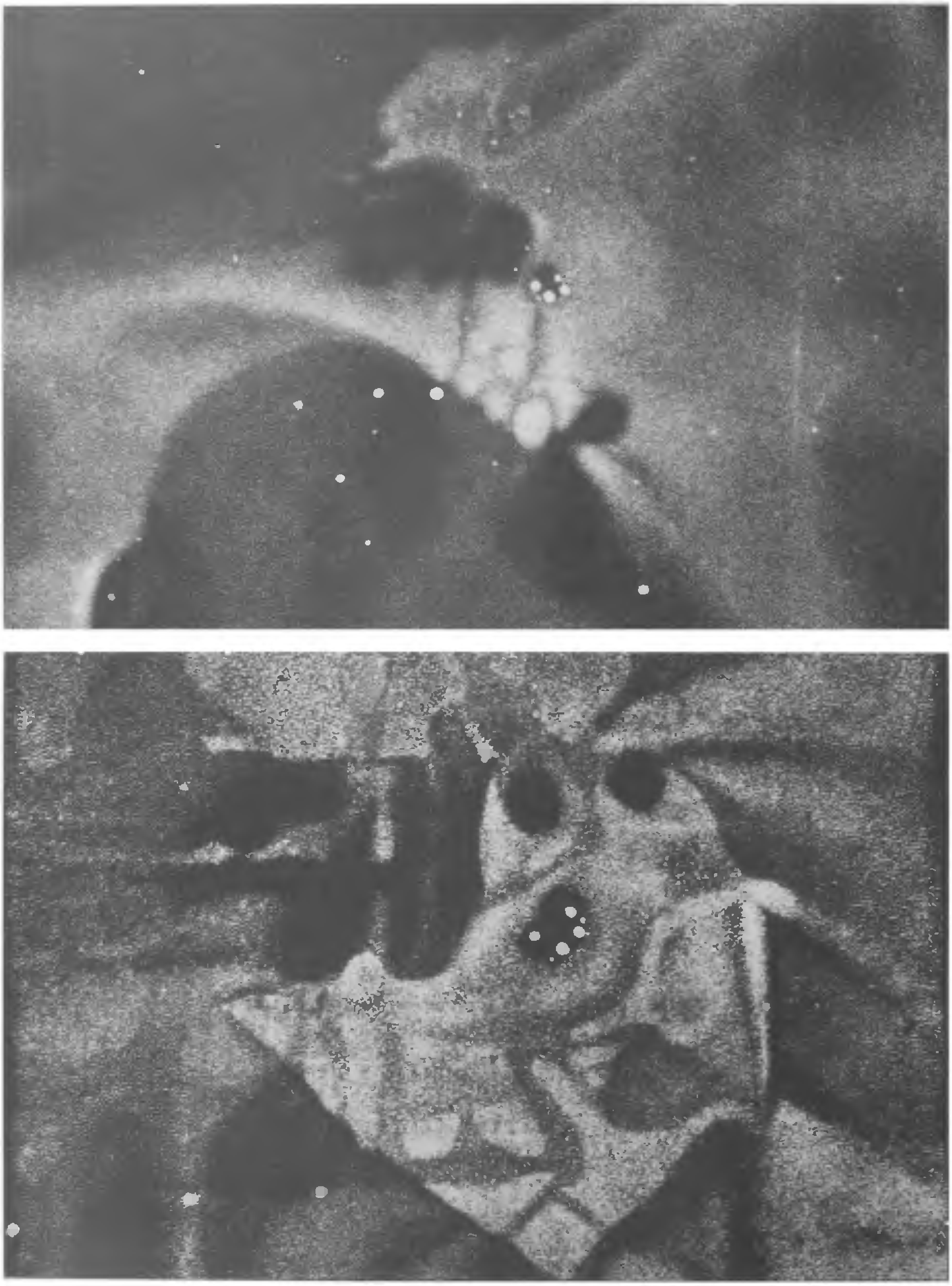

FIGURE c. Comparisons of drawings of the Orion nebula by John Herschel (top) and Lord Ross led to speculation that changes shown were real. A recent colour picture of the same region (Fig. 28 or 29 [AAT 29]) shows that much of what they saw really exists, and the differences are mainly in draughtsmanship.

> poorer part of the sky, and that not by any doubtful amount but by half or three-fourths of a magnitude. One of two things was certain, either that the eye observations were wrong, or that the stars of the Milky Way are bluer or whiter than other stars.

Referring to Pickering's[19] spectroscopic observations of the bright Milky Way stars, Gill continues:

> He [Pickering] finds thus that the stars of the Sirius type occur chiefly in the Milky Way, whilst stars of other types are fairly divided over the sky. Now stars of the Sirius type are very white stars, very rich relative to other stars in the [blue and ultraviolet] rays which act most strongly on a photographic plate. Here then is the explanation of the results of our photographic star-charting, and of the discordance between the photographic and visual magnitudes in the Milky Way.

In these extracts from David Gill's 1891 lecture to the Royal Society it is clear that he is referring to the loose collection of bright naked eye stars which form a broad band slightly inclined to the plane of the Milky Way, rather than the diffuse band of unresolved stars of the Milky Way proper. This irregular sprinkling of the brightest stars is now known as Gould's Belt and it is these stars that in the human mind and eye are readily linked to form the most conspicuous constellations.

Now that the reason for the discrepancy between the photographic (i.e. blue) and visual (yellow-green) magnitudes was understood, it became apparent that the colour difference (i.e. B–V) was a measure of the colour of a star and that this in turn was an indication of its surface temperature, a fundamental characteristic of a hot body. The mathematical relationship between the colour, temperature, and surface area of a radiator of energy was quantified by Max Planck in 1900. Planck had to invent the notion of a 'black body' (and the concept of the quantization of light!) to link these ideas, which are central to understanding the transfer of thermal radiation. His equation revealed that at very high temperatures incandescent bodies produce blueish light.

In astronomy, these concepts have been refined into the elegant graphical comparison of colour and magnitude which was devised independently by Ejnar Hertzsprung and Henry Norris Russell in the years before 1912. The Hertzsprung-Russell diagram is itself central to modern astrophysics and leads naturally to a system of stellar classification which links the colour and brightness of a star to its evolutionary state and its mass[20].

From those relationships we now know that the naked eye stars of Gould's Belt range in temperature from at least 40 000 K for young, massive O stars to perhaps 3 500 K or even less for the scattering of red giants amongst them. Though these temperatures correspond to markedly different hues, with the hottest as blue as the daytime sky and the coolest a distinct orange-yellow, we do not readily see these colours in individual stars.

The reasons for our insensitivity to colours at low light levels are now well known, but in astronomy the deficiencies of the visual system are compounded by the minute angular size of stars and the fact that the black body radiation does not give saturated colours. As well, the visual system is rather insensitive to blue light, especially when the coloured objects are of small angular size.

Once again, one is led to speculate on the present state of astronomy and physics if it had been appreciated centuries ago that the bright naked eye stars are much bluer than the sun. Would physics, and with it our appreciation of the world around us

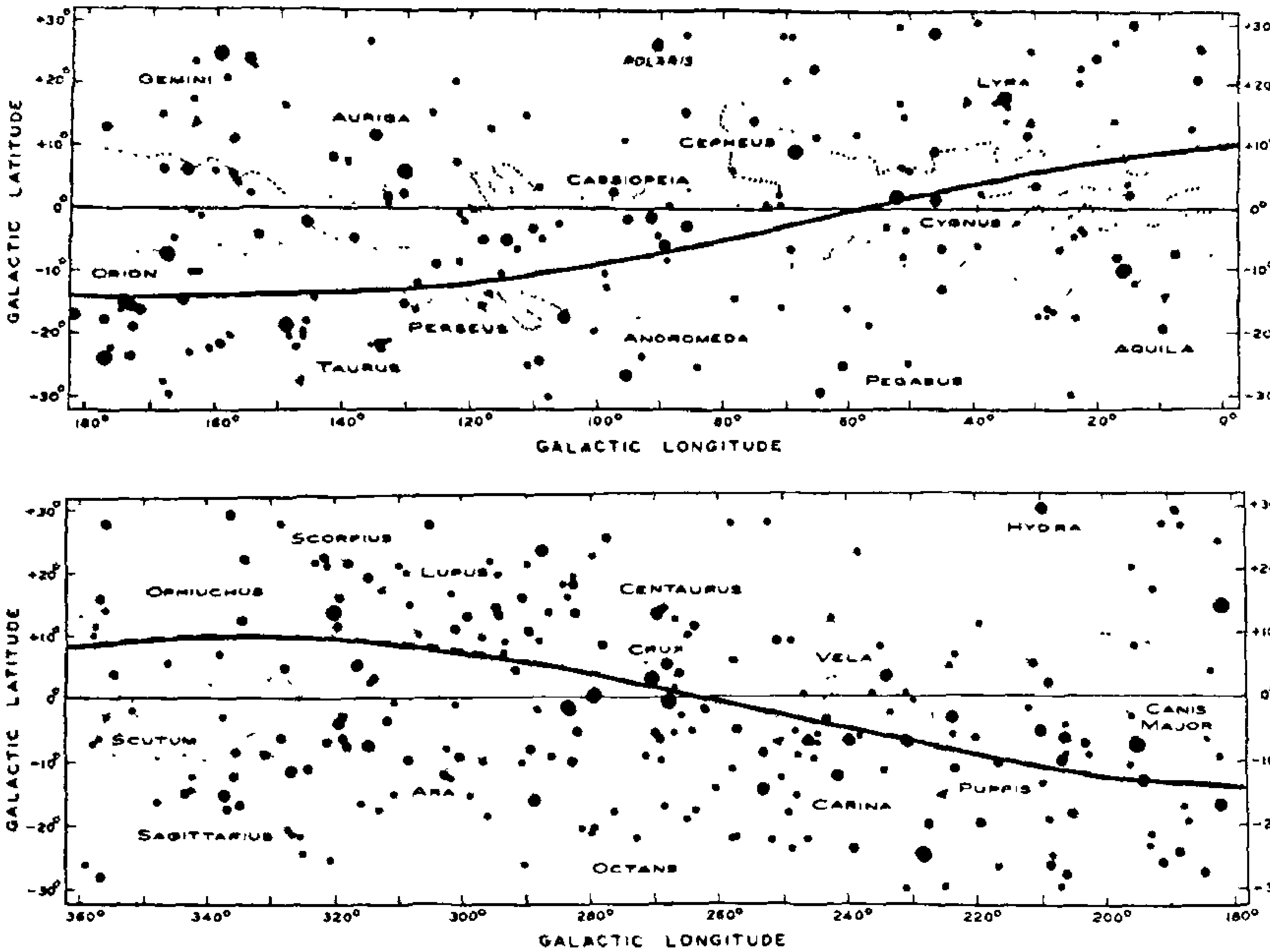

FIGURE d. Gould's belt is that broad band of bright stars that make up many of the constellations. Its center (curved solid line) is somewhat inclined to the plane of the Milky Way (dotted outline) and it represents the local distribution of the bright stars.

have been different if Planck's blackbody relationship, and its inevitable consequence, the quantum nature of light, had been uncovered much earlier in an effort to explain the colours of the stars?

This rather selective review of the deficiencies of human colour vision and its astronomical and broader scientific consequences has been undertaken in the light of numerous new colour photographs that show just the effects that our astronomical predecessors were unable to see. They also reveal many more phenomena that were not even suspected until recently. The rest of this article is an exploration of these pictures and a commentary on what they show. But first, I should briefly describe the methods that are used to reveal the colour of astronomical objects.

REVEALING THE COLOURS OF THE STARS

Photographs of stars taken with ordinary cameras and film appear at first glance to suffer from exactly the same problems as the human eye. Bright stars record as white, sometimes with just the merest hint of colour, while the faint images are often too small to be seen without a magnifier. The whiteness of the bright images has of course nothing to do with the film's lack of colour response, indeed quite the contrary. The film has responded to all the colours in the spectrum of the brighter stars, but unless the exposure has been carefully chosen, the blue-, green- and red-sensitive layers of the film are over-exposed. When all three layers respond at an equal level – in this case saturation – the end result is white.

The same effect of exposure on colour rendition is seen in all colour photography, but the brightness range of everyday scenes is much less extreme than that found amongst the stars. Not only are there no shadows or highlights to give exposure latitude but even the naked eye stars cover an enormous range of brightness, and no single exposure on any given field will give accurate colour rendering of more than just a few of them. The colours are delicate and a precise exposure is needed for stars of a given magnitude. Even for the naked eye stars, the brightness range is six or seven magnitudes, equivalent to about 10 photographic '*f*' stops, a much wider dynamic range than most photographers will ever encounter in one scene. Normal slide films will only tolerate exposure variations of around half an *f* stop before serious under-or over-exposure destroys colour rendering.

However, there are ways to step around this problem using a simple 35mm camera and ordinary colour film. The camera is set on a firm support in a dark place away from city lights, preferably on a moonless night. With the camera pointed at a constellation of interest, the lens opened to full aperture (at least *f*/5.6) and focused on infinity. The stars are allowed to trail for a few minutes. Without closing the shutter, the lens focus is shifted by some arbitrary amount, perhaps a tenth of the full focus movement, and the exposure continued for a few more minutes before the focus is moved in the same direction again. This is continued for perhaps 30 minutes until the lens' focus is at its closest distance.

The result is a photograph where the star images are divided into a number of discrete steps, each step giving a different exposure in the film plane for each of the star images, some of which will receive an exposure close enough to the optimum to reveal their true colour. The few very bright stars will produce mostly burned out steps but eventually one of the more out of focus images will appear coloured. The faint stars appear only once, as narrow focused trails, but these too are clearly seen as coloured. The results of this simple process are shown in Figures 1 and 2.

COLOUR PICTURES FROM LARGE TELESCOPES

While commercial colour films work well with black-body radiation, they are less useful for photographing objects wtih larger telescopes. Black-body colours are recorded well enough, but the often peculiar spectral distribution of light in gaseous nebulae is not well reproduced. In addition, the long exposures that low light levels demand can distort the colour balance of materials designed for much shorter exposures. Unfortunately, colour films do not respond to hypersensitizing treatments to improve their low light level performance as well as the special monochrome emulsions normally used for astronomy.

An alternative approach, which avoids the use of colour films, incorporates the oldest system of colour photography, the 3-colour separation technique devised by James Clerk Maxwell in 1861. Interestingly, Maxwell was not intending to demonstrate that colour photography was possible. He was more concerned with confirming that green, not yellow was the primary that was necessary to produce white by mixing with red and blue light[21].

In Maxwell's additive process, three separate exposures are made on to plates sensitive to blue, green and red light. In the astronomical context, pass-bands for the three colours are provided by the well-established B, V and R emulsion/filter combinations used for photographic photometry. From the three black and white negatives, monochrome positive copies are made by contact on to any suitable film material. At this stage a wide range of image manipulation techniques can be applied to enhance the image to reveal faint objects or to explore the high photographic densities produced by brighter ones[22].

The monochrome positives are subsequently enlarged, one at a time, and in register on to a positive-working colour material (Cibachrome, Ektachrome) or on to a negative film for subsequent printing by normal subtractive methods. The positives are enlarged through the equivalent of the taking filters, the red positive through a red filter, the green through a green filter etc., thus recombining the red, green and blue information in the original scene in a way that colour films cannot.

From a realistic representation of the true colours of celestial bodies, both astronomer and layman alike can find fresh relationships in familiar objects and an important third dimension to add to the morphology and brightness information of the more usual monochrome representations.

Much of the illustrative material presented here was given in the form of lectures during a visit to India in December 1989. This visit was made possible with the generous support of the Third World Academy of Sciences, the Raman Institute and the Indian Academy of Sciences. It is through the generosity of this last-named body that many of the numerous colour photographs I showed during the talks are reproduced in these pages. I am grateful to Prof. Ramaseshan for the opportunity to display them here.

The colour pictures reproduced in Part II of this article have been ordered into five groups to illustrate broad astronomical themes.

REFERENCES

1. Eder, J. M., (1945) *History of Photography* Dover Reprint, 1891, Dover Publications, New York, 1978. Gill, D., **An Astronomer's Work in a Modern Observatory** in the Royal Institution's *Library of Science* **1**, pp 362 (1970).
2. Raman, C. V. **The Physiology of Vision**, 1968, Indian Academy of Sciences, Bangalore.
3. Sloan, L. L., **The effect of intensity of light, state of adaptation of the eye, and size of photometric field on the visibility curve, a study of the Purkinje effect** *Psychol. Monogr.*, 1928, **38**, No. 1, 87 pp.
4. Hunt, R. W. G., **Light and dark adaptation and the perception of color** *J. Opt Soc. Am* 1952, **42**, 190–199
5. Ramaseshan, S., Introduction to *Scientific Papers of C. V. Raman*, **VI**, x (1988).
Raman, C. V., Scientific Papers, **II**, Physiology of Vision, p. 488 (1988).
5a. Raman, C. V., *The New Physics*, Philosophical Library, New York, p. 114
6. Herschel, W. **Account of some Observations tending to investigate the Construction of the Heavens**, *Phil. Trans*, 1784, **74**, 437–451.
7. Hoskin, M A. *William Herschel and the Construction of the Heavens*, 1963, Oldbourne, London.
8. Herschel, W. **On the Construction of the Heavens** *Phil. Trans.*, 1785, **75**, 213–266.
9. Bica, E., Alloin, D., and Schmidt, A. A., **Star formation history and chemical enrichment in the nuclear regions of M31 and its dwarf companions** M32 and NGC 205 *Astron. Astrophys.*, 1990, **228**, 23–36.
10. Herschel, W. **On Nebulous Stars, properly so called** *Phil. Trans*, 1791, **81**, 71–88
11. Herschel, J. F. W., *Outlines of Astronomy* 6th edition, Longman Green, Longman and Roberts, London 1859.
12. Arago, D. F. J., *Popular Astronomy*. Translated and edited by W. H. Smyth and R. Grant 1855, (Longman Brown, Green and Longmans, London, 1855).
13. Huggins, W. and Miller, W. A., **On the spectra of some of the fixed stars** *Phil. Trans*, 1864, 413–435.
14. Secchi, A., **On the Spectrum of the Nebula of Orion** *Mon Not. R. Astr. Soc.*, 1864, **25**, 154.
15. Huggins, W. Comments on a paper by Secchi *Mon. Not. R Astr. Soc.*, 1864, **25**, 155–157.
16. Weaver, H. F., **The development of astronomical photometry** *Popular Astronomy*, 1946, **54**, 389–404.
17. Pickering, E. C., 11 *Mem. Am. Acad. Arts and Sci.*, 1888, 203.
18. Schabaerle, J. M., On the photographic brightness of the fixed stars *Publ Astron. Soc. Pac.* 1889, **1**, 51–64
19. Pickering, E. C., **Preparation and Discussion of the Draper Catalogue**, *Annals Harvard Coll. Obs*, 1891, **26**, Pt 1.
20. DeVorkin, D. H., **Stellar evolution and the origin of the Hertzsprung Russell diagram** Chapter 6 (pp 90–108) in *Astrophysics and Twentieth Century Astronomy to 1950' Part A*, 1984, ed. O. Gingerich, Cambridge University Press 1984.
21. Maxwell, J. C., **On the theory of the three primary colours** *Brit. J. Phot.*, 1861, **8**, 270.
22. Malin, D. F., **The developing art of star photography** *New Scientist*, 1989, **120**, 23–28
23. Malin, D. F, **Unsharp masking** *AAS Photo-Bulletin* No. 16, 1977, 10–13.