Part II – Commentary on the Colour Pictures

A. THE COLOURS OF STARS AND THE GALAXY

The step-focus photographs, reproduced as Figures 1 and 2, reveal the colours of all the naked eye stars in two wide fields about 25 degrees across, one centred on the stars of Orion's belt, the other on the eastern border of Crux, adjoining Centaurus.

In **Figure 1** the photograph has been oriented with north at the left and west at the top. It shows all the stars from eighth magnitude objects well below the threshold of naked eye visibility to the striking yellow-orange of Betelgeuse and dazzling blue of Rigel, both over six magnitudes brighter. Of the several hundred stars visible in the photograph, all the brightest are clearly blue, with the obvious exception of Betelgeuse (lower left) and the bright red streak of the Orion Nebula, the central 'star' in the group of three forming Orion's sword handle. To the left of this group are the three prominent stars of Orion's belt, Alnitak, Alnilam and the extremely hot Mintaka at its western (top) end. Both Mintaka and Bellatrix, in Orion's left shoulder (top left of the picture) appear to be a slightly deeper blue and are therefore hotter than the other prominent stars of this most distinctive constellation.

With modern knowledge of the spectral classification of stars we can confidently say that the bright stars we see in the photograph are young, massive and very rare. The reason that they are so obvious is that these stars are extremely luminous, some with a luminosity approaching a million times that of the sun. We can therefore see them over enormous distances. That a small fraction of the bright stars are orange rather than blue is also not unexpected, but not easily demonstrated without a simple photographic ruse such as this. These are young stars that have evolved to their 'red giant' stage, a brief, final interlude in the short life-span of massive stars, so we see only a few of them amongst the blue stars of Gould's Belt.

It should be emphasized that these 'red' stars are not red at all. They are no redder than a tungsten-halogen projector lamp which has a similar colour temperature, and they are actually much bluer than the domestic tungsten filament lamps we use in our homes, neither of which we normally regard as particularly red. Both red giants and tungsten lamps are accurately rendered as orange-yellow on the daylight-balanced film used for these pictures. Astronomers call them red because the zero point in the commonest colour index system is taken as a star with a surface temperature of 10 000 K, which to our eyes, and to daylight photographic materials, would appear distinctly blue. In the absence of colour pictures to contradict them, astronomers have fallen into the way of calling cool, massive stars 'red giants', a name that is now unlikely to be displaced.

The stars of the Southern Cross seen in **Figure 2** are accompanied by their distinguished companions Alpha and Beta Centauri. These stars are approximately 30 degrees from the south celestial pole and therefore seem to move across the sky more slowly than those in Orion which straddles the equator. During the half hour exposure used to make Figure 2, the lens focus was moved in about twelve steps, as opposed to the nine or so in the Orion picture. North is at the top and east is to the left in this picture.

The nearest of all the bright stars (except the sun) is Alpha Centauri. This multiple system is the most easterly of the two Pointers. Apart from Alpha Aurigae (Capella), Alpha Cen is the only bright star in the sky with a colour similar to that of the sun. Alpha Cen therefore appears colourless in the step focus picture, irrespective of exposure level, giving us confidence that the colour balance of the film is accurate. This lack of colour is in sharp contrast to the rich blue of Beta Centauri which, while only half a magnitude fainter, is over 100 times more distant and therefore about 10 000 times more luminous.

This observation underlines the enormous difference in the intrinsic luminosities of young, extremely hot, giant stars like Beta Centauri when compared with less massive stars such as the Sun and Alpha Centauri. This simple experiment reveals in a dramatic way something which is not apparent to the human eye and which was only dimly perceived by Pickering and his contemporaries. The bright stars of Gould's Belt are mainly blue with a few bright orange-yellow stars scattered between.

The colour-magnitude diagrams of modern measures of star colours show that highly luminous blue stars of class O and B are extremely rare while yellow M and K giants and supergiants are even rarer. Such stars have short but brilliant careers, which often end in the most catastrophic failure. Massive stars destroy themselves as supernovae. By comparison, intrinsically faint, low mass stars like the sun are vastly more numerous, partly because they survive for billions, rather than millions of years. They end their lives in a less dramatic way, as we shall see. But it is the few brightest stars that dominate the naked eye appearance of the night sky, while the multitudes of less luminous stars are hardly visible.

The abundance of light from the blue stars in the arms of a spiral galaxy becomes more evident when we look at colour pictures of galaxies that are known to be like the one we inhabit. In **Figure 3** we see Messier 83, one of the finest and nearest examples of a spiral galaxy anywhere in the sky. Because by chance we see from above one of its poles, it is ideally placed for us to study the anatomy of a stellar system that is similar to the Milky Way.

At a distance of about 8 Mpc, M83 is close enough for a few of the most luminous stars to be seen as individuals and many clusters of such stars are easily visible. They give the spiral arms of M83 a clumpy texture and distinctly blueish hue. As in the Milky Way, young stars such as these are often formed in groups and the presence of many brilliant clusters of blue stars in the spiral arms emphasises the extreme youth of these distinctive features.

Forming the inner curves of the spiral arms are large numbers of pinkish nebulae, each one a region where young stars are intimately associated with the gas and dust in which they were born. Most of this material is hydrogen which is excited by ultraviolet radiation from the hot stars, causing it to fluoresce a characteristic red colour. And finally, on the inside of the spiral arms, closely associated with the visible nebulae, there are found long straggling clouds of dust, seen as dark yellow-brown in this colour picture.

The nucleus of M83 has a colour quite unlike that of the outer parts. In the central regions of the galaxy there are relatively few of the highly luminous stars that dominate the spiral arms. Instead, there is a high concentration of stars which are old, cool and yellow. Although these stars are individually much fainter than the sprinkling of blue giants further out, towards the centre they are much more numerous and their light dominates the region around the nucleus. The colour picture confirms what we already know about the distribution of stars in spiral galaxies in a spectacularly satisfying way.

Like the Milky Way, M83 is a flat galaxy. If we were able to turn it on its side, we would see just how slender it is. We would also see the dust lane that in most spirals is tightly constrained to the galactic plane. While we cannot turn M83 around to look at it edge-on, we can find other examples of spiral galaxies that are suitably oriented. One of these is NGC 3628, **Figure 4**. The central bulge of this galaxy seems to have more stars than either the Milky Way or M83 and NGC 3628 is distinctive in another way. It has been involved in at least one close encounter with near-neighbours and the outer parts of the spiral arms and the prominent dust lane have been disturbed and broadened.

The picture shows clearly the colour effect produced by the dust lane. As we shall see later, this deep yellow-brown colour is typical, and results from the absorption of the blue component of the light of stars beyond it. Where the dust is thickest, no light passes at all. Along the dust lane are a few pink nebulae indicative of star formation.

Take an imaginary journey towards the nucleus of NGC 3628 in the plane of the dust. If you stopped at some arbitrary place part way in and made a long-exposure picture, you might well see something like the scene in **Figure 5.** But this is a view towards the centre of our own Galaxy, photographed with an ordinary camera. It covers about 45 degrees of the southern sky and shows the broad, irregular dust lane that hides so much of the galaxy from view. It also shows that the northern part of the bulge in our Galaxy is almost completely hidden from us by a dust cloud. What little light does penetrate is very deficient in blue, an effect that astronomers call reddening, but not to be confused with the Doppler redshift due to movement of the light source away from us.

The uniform scattering of resolved stars we see are probably nearby members of the spiral arm of which the sun is a member, and we look through them to an inner spiral arm. Here and there are red emission nebulae; the most prominent, at the left of the picture, is M8, the Lagoon nebula and its associated nebulae, which are seen more clearly in Figures 22–26. On the right of the picture are two fainter emission nebulae, NGC 6334 and 6357, embedded deep in the dust of the inner spiral arm. These are seen in Figure 14. The centre of our Galaxy is completely hidden at visible wavelengths, but lies on a line roughly halfway between M8 and NGC 6334–57.

The bright cloud of unresolved stars in the lower half of the photograph is a spectacular sight during the southern hemisphere winter. They are very visible evidence of those stars that congregate in huge numbers in the bulge of our Galaxy. Though they are not completely hidden by intervening dust like the equivalent northern bulge, our view of them is still strongly affected by interstellar obscuration. This was well known to Walter Baade, who studied the Milky Way extensively from the Mt. Wilson Observatory in California before and during the Second World War. He was the first to recognise that there are two basic types of stars in most galaxies, those intrinsically faint, relatively cool stars that are found in huge numbers in the Galactic bulge, which he defined as Population II, and the much rarer, highly luminous stars of Population I that are found in the spiral arms. We see examples of Population I stars in Figures 1 and 2.

To thoroughly characterise the Population II stars, Baade selected an area of the bulge centred on the globular cluster NGC 6522, which is in the centre of **Figure 6.** He believed that the interstellar obscuration was at a minimum in that direction and that he could see deep into the Galactic bulge to sample stars close to the galactic center, 8 700 pc distant. This patch of sky is now known as Baade's Window. There are two globular clusters in the photograph; NGC 6528 is to the left and is partly obscured by dust. In the near foreground about 40 pc distant is the bright orange K0 giant star Gamma Sagittarii.

A wider view of the star clouds of Sagittarius is seen in **Figure 7**, which also contains Baade's Window. The complex nature of the dust clouds is evident, as is the colour effect of increasing dust thickness. Where the stars appear fewest, on the left of the picture, they also seem yellowest. This, and the previous photograph were made from the same set of plates taken with the UK Schmidt telescope, which provides a wide field of view, in this case six degrees from top to bottom. Towards the top of the picture is a tiny dark cloud, catalogued as number 86 in the catalogue of E. E. Barnard, a self-taught American astonomer-photographer who was fascinated by the dark spaces in the Milky Way, and whose photographic work did so much to establish their nature. In a photograph taken with the Anglo-Australian telescope (**Figure 8**) Barnard 86 is shown in much more detail.

It can be seen that this dark space, of the kind that Herschel believed was evidence of the ravages of time on the fabric of the Milky Way, has a brownish, ill-defined edge to it where stars seem to fade away, exactly the signature expected of a semi-opaque lens-shaped dust cloud. In the same field of view is a young open cluster of stars, NGC 6520, the stars revealing in their colour the presence of young, massive stars at various stages of their evolution. Many such open clusters of widely differing ages can be found throughout the Milky Way. It is the study of the colours of the stars in clusters of this kind, where the members of group are all at the same distance and have formed at about the same time and from the same materials, that astronomers learn about stellar evolution. Fortunately, not all are seen against such complex backgrounds, e.g. Figure 16.

B. DUST, GAS AND REFLECTION NEBULAE

In **Figure 9**, another wide angle view of the Milky Way shows subtle changes of colour caused by irregular interstellar absorption across a broad field of stars. At the left side of the picture is the bright star-forming region Messier 17, on the right is a less spectacular emission nebula that Messier did not catalogue. This is the complex seen in more detail in **Figure 10** around the two blue reflection nebulae NGC 6589-90. These two nebulae surround stars caught in the dust which is evident throughout the region. The stars themselves are not hot enough to produce a large emission nebula, but they are luminous enough for their light to be scattered over a wide area by the dust grains. In the centre of the picture, the dust thins so we can see more stars, and the traces of hydrogen that remain are illuminated by a bright star that is hot enough to excite an emission nebula. In this nebula, the scattered blue light and red fluorescence blend to a soft magenta shade.

Perhaps the most memorable image created by the interplay of starlight, gas and dust is that of the Horsehead nebula in Orion. A UK Schmidt view of this is shown in **Figure 11**. The Horsehead itself is a partially opaque projection from a much larger dark cloud that is illuminated by Sigma Orionis, the star at the top right of Figure 11. Sigma's radiation is eroding the molecular cloud, releasing atomic hydrogen which provides the vivid red background of IC 434 against which the horsehead shape is seen. To the left of the picture is the grossly over-exposed image of Zeta Orionis which is in the foreground and plays no part in illuminating the nebula. However, its swollen image and cross-like telescope artefacts partly hide the curious yellowish nebula NGC 2024. The photograph also contains a number of blue reflection nebulae, the most conspicuous being NGC 2023, near the base of the Horsehead.

The red nebulosity which characterises hydrogen emission is not a pure red. As well as the dominant red Hα line, weaker lines are present, most prominently the Hβ line in the blue part of the spectrum. Thus the colour of the emission nebula is a mixture dominated by red but with a blue component, i.e. a shade of magenta. As we have seen, the tiny particles that comprise interstellar dust preferentially absorb blue light, so where we see emission nebulosity through dust its colour is changed from magenta to a fainter but purer red by selective absorption. This effect can be seen in **Figure 12** in the lower jaw and mane of the horsehead shape where the dust does not completely hide the nebula beyond.

An even more dramatic demonstration of interstellar reddening in a red nebula is shown in **Figure 13.** Though these two objects appear side by side on the sky, the nebulosity associated with the remarkable cluster NGC 3602 (left) is on the far side of the Carina spiral arm of the Galaxy at a distance of 8 Kpc, and is seen through several magnitudes of dust. Its apparent neighbour, NGC 3576 on the other hand, is less than half as far away and is hardly obscured at all. The difference that interstellar absorption makes to the colour of these objects is obvious from the colour pictures. The two nebulae first seen in Figure 5 are seen in more detail in **Figure 14.** They are also embedded in dust and their colour is similarly 'de-blued'. So heavy is the absorption of blue light towards these objects that the bright blue stars responsible for the nebulosity are quite inconspicuous.

One of the nearest of the dark clouds that hide so much of the Galaxy from us is a prominent naked eye object to southern observers, and is nowadays known as the Coalsack. It is all the more prominent because it lies alongside the brilliant asterism of the Southern Cross. It is seen clearly in **Figure 15** which is a long exposure taken with an ordinary camera. Though it shows stars much fainter than can be seen with the unaided eye, the Coalsack, near the centre of the picture, is still clearly visible by virtue of the stars it hides. Also evident, scattered across the picture, are numerous open clusters of stars. In a large telescope these clusters are a magnificent spectacle, especially where some of the brighter members have evolved to the red giant stage as in **Figure 16.** This cluster of young stars is NGC 3923 in Carina, and traces of the nebula from which they probably formed can still be seen to embrace it.

Not all nebulosity associated with open clusters reveals the remains of the material which gave rise to the stars. In the case of the Pleiades, seen in **Figure 17,** the group of stars seems to have drifted into the tenuous dusty outskirts of a molecular cloud. The wispy 'combed hair' structures are not associated with the stars, but are the result of the alignment of the tiny particles in the interstellar magnetic field. The alignment was probably present long before the stars arrived to reveal it.

The blue colour, as in many reflection nebulae, comes from selective scattering (Rayleigh scattering) by particles much smaller than the average wavelength of the starlight. One of the bright Pleiads, Merope (lower left) is the closest to the invisible molecular cloud, whose presence has been detected by radio observations. This star seems to be illuminating particles more numerous and perhaps larger than those elsewhere. The reflected light is therefore more like that of the star from which it came and much less blue than the rest of the nebula. Once again, the colour reveals a subtle effect that is not visible in black and white.

Solid particles between the stars are believed to be commonplace, but are very difficult to detect at visible wavelengths. The recent supernova in the Large Magellanic Cloud has provided an unexpected chance, not only to detect them, but to map their three-dimensional distribution in space. The brilliant flash of the supernova was detected in February, 1987. The supernova reached maximum brightness in May of that year (Figure 49) but has now faded so that it is fainter than the star that exploded. This brief, intense flash of light travelled 170 000 years before being detected on earth. However, some light has been deflected by tiny dust particles near, but not, on our line of sight to the supernova. This light has travelled further to reach us and its arrival was therefore delayed.

The dusty regions encountered are two distinct concentrations of particles 400 and 1 000 or so light years in front of the supernova. The dust, itself the detritus from massive stars, has probably been swept up by earlier generations of stellar outbursts. The two dusty regions are seen as two concentric circular light echoes whose colour accurately reflects the yellowish hue of the supernova at its brightest, when the plates for Figure 49 were taken. The rings expand with time and reveal the morphology of the dust layers increasingly distant from the line of sight, providing an unparalleled opportunity to map its three-dimensional distribution. The light echo picture was made by photographically subtracting three black and white images taken in blue, green and red light from three similar plates taken before the supernova appeared, and combining the three derivatives into a colour picture.

There are many sources of the solid particles between the stars. Probably the most prolific are the outer envelopes of massive, cool red giant stars such as Antares, seen at lower right in **Figure 19.** In this picture, the star itself is invisible, hidden in a reflection nebula of its own making. Eventually, the particles of refractory materials, that have condensed out of the distended atmosphere of the star will gather into cold, dark clouds like the ones seen elsewhere in this photograph. Where the dust is dense enough to protect its interior from destructive ultraviolet photons, it is cold enough for most volatile materials to condense on the surfaces of the dusty particles. It is in such places that astonishingly complex organic molecules form and survive.

As in the Pleiades, occasionally stars drift by to illuminate the outskirts of the molecular clouds, producing the usual shot silk effect in a blue reflection nebula. Here and there, this light is mixed with emission nebulosity or attenuated by yet more dust, producing an astonishing range of colours. But behind the colourful curtains can be seen the dark clouds, pregnant with young stars not yet visible. It was this part of the sky that William Herschel thought was a void through which he could see the universe beyond. His eyes were not sensitive enough to respond to the nebulosity that we now know fills the field. What he saw was not an empty, distant universe, but a nearby stellar nursery, for the moment merely reflecting starlight, but soon to produce its own.

Reflection nebulae are often faint because the particles that are responsible are few and far between and are, in any case, inefficient reflectors. Usually, they are only capable of reflecting starlight, but one example has been found of a reflection nebula reflecting the light from another nebula. In **Figure 20** we see the yellowish glow of the Orion nebula (Figure 28) reflected in a nearby dusty cloud known only as NGC 1977. Black and white pictures of this scene show its complexity, but give no hint that the illuminating source is another nebula. The nebulosity of NGC 1977. **Figure 21** is itself quite a beautiful mixture of reflection and emission nebulosity, but completely out-shone by the Orion nebula only one degree away. Both nebulae are seen in Figure 28.

C. STAR-FORMING REGIONS

The Trifid nebula, Messier 20, is perhaps the best known example of an emission nebula which is associated with a reflection nebula, seen as the faint bluish haze to the left of **Figure 24**. However, rather surprisingly, recent deep colour pictures made from UK Schmidt plates (**Figure 22**) reveal a faint reflection nebula completely encircling the red emission region. Both nebulae are produced by the tiny group of young, massive stars at the centre of **Figure 23**, near the junction of the three dark lanes that give the nebula its name. These extremely luminous stars produce enough ultraviolet light to excite the roughly spherical emission nebula seen in Figure 22. Beyond that, much hydrogen remains, but all the UV capable of exciting it has been absorbed. Only visible light emerges, and some of its blue component is scattered by the tiny motes of dust associated with the gas. Thus we see an emission-bounded nebula – a Stromgren sphere – surrounded by a reflection nebula, another phenomenon made visible by colour photography.

In **Figure 25** we see the Lagoon nebula (Messier 8), just visible to the unaided eye as a faint fuzzy patch in the southern constellation of Sagittarius, not far from the conspicuous star clouds seen in Figure 7. The centre of star-forming activity in M8 is now in the western (right) side, but the cluster of young stars in the eastern half testify to a recent burst of star-forming activity there. Those stars seem to have blown the dust in the region into dark swathe dividing the two parts of the nebula. The dark lane crossing the bright nebula gives the object its popular name.

M8 and M20 are probably part of the same gassy complex that is seen in **Figure 26**. Here we see both emission and reflection nebulae set against the clouds of yellow stars that swarm around the nucleus of the Galaxy. The dark spaces between them are the unlit portions of one of the numerous molecular clouds that hide so much of the Galaxy in this direction. Where stars have appeared, the dark molecular clouds come to life as beautiful nebulae, often revealing the dust as sinuous dusky lanes crossing the brightest parts of the luminous backdrop.

The nearest and best-studied star-forming region is that in Orion. A wide angle view is seen in **Figure 27** which shows the Horsehead nebula and (at left) two of the three brilliant stars of Orion's Belt. Numerous faint nebulosities are evidence of the abundant reflective material that is scarcely illuminated at all. The part that provides some of the best-known images in astronomy. One of these nebulae is so bright that it is burned out on the three-colour photograph made directly from the three UK Schmidt plates that were used to make **Figure 28.** With unsharp masking[23] the Orion nebula comes to life and reveals as a distinctive red glow that part of hydrogen cloud that is directly illuminated by the bright stars in its brilliant core.

The stars themselves are seen in **Figure 29**, made from short exposure plates taken with the AAT. This tiny group of stars, known as the Trapezium group from their configuration, is responsible for one of the few nebulae that can be seen with the unaided eye. In the brightest parts of the Orion nebula, the green line of oxygen is as strong as the red hydrogen Balmer *alpha* line. These emission lines dominate the central regions and together are responsible for its distinctly yellow hue. On ordinary colour film, this region is normally seen only as red because the blue-green oxygen line falls on a blind part of the spectral sensitivity curve.

The complex structures and filaments seen here have been emphasized by unsharp masking to confirm these stars as the source of an energetic outflow in the nebula. Such outflows are a normal consequence of the birth of massive stars. The radiation and stellar winds from them will eventually disperse the surrounding nebula from which they came. This effect is clearly seen in the aptly named Rosette nebula, **Figure 30.** Here, NGC 2244, the cluster of stars at its centre, has created a large cavity, several parsecs across, and will eventually blow it away completely, leaving a brilliant, young open cluster ornamenting the constellation of Monoceros (**Figure 31**).

All these nebulae give ample evidence of dust intimately associated with star formation. This is also evident in **Figure 32**, the striking Cone nebula, also in Monoceros. The cone itself is similar to the Horsehead nebula (Figure 12), a dust protruberance illuminated by a bright star, in this case S. Monocerotis, off the top of the picture. As in the Horsehead, the vivid red back-illumination is provided by the glowing surface of a molecular cloud illuminated by several very hot stars. This image is one of the few made at optical wavelengths to reveal the presence of newly-formed stars, not yet free of their dust cocoon. They are not seen directly, being well hidden within the dusty backdrop. They reveal their presence by the colour they impart to the dust that embraces them. The several small, distinctly yellow nebulae are the result of the light from these young stars strongly scattered and reflected by the dust, emerging feebly from chinks in the obscuring veils. Eventually, these stars too will blow away their dusty fronds and become as visible as those in the foreground which were formed in a similar dark place less than a million years ago.

One of the most spectacular stellar nurseries, only visible from southern latitudes, is the Carina nebula, NGC 3372. It is about 2500 pc distant, yet is visible to the naked eye, mainly because of the large number of very luminous stars it contains. The spreading tendrils of the nebula are clearly visible in **Figure 33**, a picture made from UK Schmidt plates. As well as the nebula, this wide-angle image reveals the enormous number of stars visible in this direction. The region is not only famous for its nebula, remarkable though it is. It contains some of the most luminous stars in the galaxy. No fewer than four of them are seen in the closer view of the inner part of the Carina Nebula provided by **Figure 34.**

This part of the sky also contains one of the most remarkable stars ever seen, even more remarkable for the fact that it was once the second brightest star in the sky, only outshone by Sirius. This star and its nebula were the subject of much speculation by Sir John Herschel who observed it from South Africa when it was near its brightest in 1834. His sketch of the star field and the nebula is overlaid as a negative on Figure 34 and is discussed further in the next section.

The brilliant stars in the Carina nebula seem to be scattered across a considerable volume of space and apart from clusters such as Trumpler 14, in the upper right of **Figure 34,** there are no obvious concentrations. However, in the same constellation there is a most remarkable object where a huge number of very hot stars are concentrated into a very tiny volume. Unfortunately, this cluster, NGC 3602, illustrated in **Figure 35,** is heavily obscured (see also Figure 13), so is less well studied than might otherwise have been the case.

Within this compact cluster are many Wolf-Rayet stars, some of the hottest and most luminous stars known. They must have formed there recently, because their extreme properties ensure a short life. No other such group is known in our own Galaxy and if NGC 3602 could be seen without obscuration it would be spectacular indeed. However, because such concentrations of stars are so luminous they can be seen over vast distances, even in galaxies beyond the Milky Way such as the Large Magellanic Cloud (LMC).

In the LMC is one of the most spectacular and enormous star-forming regions known anywhere. It is centred on the 30 Doradus region in the eastern LMC, and is seen as the brightest nebulosity to the left of Figure 51. A closer look is presented in **Figure 36** which reveals the huge number of bright stars that surround it. This rich constellation is over 50 Kpc distant, so each of the bright stars visible in the photograph is many thousands of times more luminous than the sun. If the sun was there it would be too faint to be seen on this picture. On the left of the photograph, and wreathed in the tangled nebulosity of the Tarantula nebula, is the region where star formation is at its most intense.

At the centre of the Tarantula, burned out on this picture, is the compact cluster 30 Doradus. Its name suggests that it is a single star, and it was long thought to be so, since even the most powerful telescopes could not resolve it. But if it was single, its apparent brightness suggested that it was a most extreme specimen, with a mass perhaps a thousand times that of the sun. Such stars are unlikely to be stable enough to survive and another explanation was sought and eventually found. Special image recording and analysis techniques (speckle imaging) have now resolved the central 'star' in 30 Doradus into several components, each extreme in their own way, but not implausible in the way that an unresolved 30 Doradus was. Some of these stars are Wolf-Rayet types like those in NGC 3602 (**Figure 35**) and the whole cluster is now believed to be very similar to the NGC 3602 group, but richer in stars and six times more distant.

The nebulosity in a region with so many luminous stars is buffeted about by supernova explosions and intense winds from their surfaces. Sometimes, the stars blow away the nebulosity to form cavities relavitely free from nebulosity. On black and white pictures, these can be hard to distinguish from dust patches that also appear as 'clearings.' In colour however, there is no such ambiguity. The dust patches in **Figure 36** are obviously yellow-brown in colour and can readily be seen scattered across the nebula.

While star formation now seems to be concentrated at the eastern end of the LMC, that was not always the case. To the north of the 30 Doradus nebula are clouds of stars that appear distinctly blue on colour photographs such as **Figure 37**. These clouds and clusters are still associated with some gas and many nebulae can be seen. The clumps of stars and their lingering nebulae are a few tens of millions of years old, and are very immature on the cosmic time scale. In a few million years time the 30 Doradus region itself may look like this as the centre of star formation moves elsewhere in the LMC.

In our Galaxy, globular clusters are very old collections of predominantly yellowish stars that are thought to have formed before the Milky Way itself, well over 10 billion years ago. Two examples are seen in the nebulosity near Antares in Figure 19. In the LMC, the globulars are much younger, and their integrated colours are bluer. These clusters typified by Hodge 11 (**Figure 38**), have generated a lot of interest over the years, and photographic photometry has been used to measure their colours. When the plates used for such photometry are combined into a colour picture, Hodge 11 reveals the presence of a large number of blue stars.

D. MASS LOSS AND ENDPOINTS IN STELLAR EVOLUTION

The LMC is well placed for us to see the components of a modest sized irregular galaxy in considerable detail. This is of interest because the LMC is in many ways unlike the other galaxy we are familiar with, the Milky Way. One of the curious features of low-mass galaxies are huge wind-blown bubbles that seen to have no counterpart in the Milky Way, but are seen in galaxies like the LMC. One of the biggest is seen in **Figure 39**. Henize 70 is over 100 pc across and at its centre is a group of hot stars that are responsible for the outflow of energy that has created the bubble. The visible surface of the sphere is the region where the almost stationary interstellar medium of the LMC has been assaulted by the 3000 km per second winds from the stars near its centre. The interface is a thin region that releases energy from the cluster of stars within as a faint, almost spherical nebula.

This kind of outflow is a common feature of heavyweight stars, though it is not always so dramatically evident. It is a manifestation of mass loss, whereby such stars shed a substantial fraction of their substance relatively rapidly. Since very massive stars, those over 10 or so times heavier than the sun, are relatively unstable, mass loss increases their stability and prolongs their life. Some stars eject energy into the interstellar medium relatively steadily, like the almost hidden star near the center of the spherical shell in **Figure 40.** This same star also illuminates a region of relatively undisturbed hydrogen to create the wispy red nebula.

Other stars have episodes of mass loss so vigorous that they are seen to eject nebulae. Sometimes these are symmetrical, like the one around the Wolf-Rayet-like star HD 148937 seen in **Figure 41.** The two lobes of the nebula are so bright that they were given two catalogue numbers, NGC 6164-65. A deeper picture, **Figure 42,** which was made from the same set of plates as Figure 41, has NGC 6164-65 at its centre but shows evidence of an earlier outburst in the faint, crenellated nebula around part of the photograph.

One of the most dramatic stars known to undergo sporadic mass loss is the remarkable object Eta Carinae, referred to earlier. It had long been known to be an irregularly variable star and, by good fortune was approaching its brightest when Sir John Herschel was observing the largely unknown southern skies from his observatory in Cape Town, South Africa, in the early 1830's. He took particular note of this newly conspicuous star and the curious nebula alongside it and produced a sketch of what he saw. Herschel's drawing is overlaid as a negative on the modern colour picture, Figure 34. Today, the star Eta has faded by a factor of over 1 000 to well below naked eye visibility, and the eastern (lower) side of the nebula that Herschel saw to be very bright has also disappeared.

This odd behaviour is explained by the extreme mass of Eta Carinae. In Herschel's time at the Cape, the star had suddenly ejected a substantial part of its outer layers, effectively increasing its size and thus its apparent brightness. The newly brightened star illuminated one side of a nearby dust cloud that soon became known as the Keyhole nebula, more clearly seen as the central shape in **Figure 43.** During the next few years, the material that the star ejected cooled and became opaque, masking the light of the star within, which was thus seen to fade. As it faded, the nebula it illuminated, also disappeared.

In the 155 years since Herschel's observations, the ejected material has continued to expand and is now visible as the small ragged shape around the star, differentiated by its colour from the background nebulosity. Some light from the star escapes, as evidenced by the diffraction spikes in **Figure 44,** but most is absorbed by the opaque nebula and re-radiated as heat. This nebula is therefore very bright at infrared wavelengths. Within it is an even smaller nebula, known from its manikin shape as the Homunculus. It is shown in **Figure 45,** a very high resolution image, and one of the few colour photographs taken from the *f*/8 focus of the AAT.

In many massive stars, loss of their material continues as they change from blue into swollen yellow-orange stars, generally known as red giants or super-giants. The yellow nebula around Antares in Figure 19 is clear evidence of the enormous cloud of solid particles associated with such a star. Another example is seen in **Figure 46** which is a reflection nebula around HD 65750. As in so many stellar ejections, the nebula is bi-polar. However, the red loop is a reflection of a different kind, a halation ring from light scatter within the red-light plate that was used to make the colour picture.

Massive stars may undergo several stages of mass loss, finally ending their lives as supernovae. Low or moderate mass stars such as the sun, or those high mass stars that have undergone substantial mass loss, expire in a slightly different way. They, too will lose their outer layers, to produce planetary nebulae which often have a satisfying symmetry as in the Helix nebula in **Figure 47.** The removal of the outer layer of the star reveals the much hotter core beneath, and for a relatively short time this radiates ultraviolet light of sufficiently high energy to ionize the stellar ejecta around it. The colours therefore tell of the composition of the outer layers of the original star. Green, and some of the red is from oxygen, while nitrogen, hydrogen of course, and sulphur also contribute.

But the naked core of the star, now described as a white dwarf, no longer retains the lighter elements necessary for further fusion reactions to keep it shining. It cools quickly and after a few tens of thousands of years fades from sight at visible wavelengths. As it cools, the nebula around it will also disappear and disperse. Continuing the theme of symmetrical outbursts, the unusual planetary nebula NGC 6302 **(Figure 48)** has been likened to a butterfly. It is likely that the magnetic fields of the original star have dictated the form of the star's last gasp.

Returning to the more massive stars, they end their lives in a much more dramatic fashion, exploding as supernovae. Like planetary nebulae, they return material enriched in elements heavier than hydrogen and helium back into the mixing vessel of the galaxy to eventually gather in cold, dark clouds and collapse into new stars. But planetaries derive from low mass stars whose internal fusion reactions can only produce elements with atomic numbers up to iron, and precious little of that. However, from primordial hydrogen and helium they do produce carbon, nitrogen, oxygen, sodium, potassium, chlorine, the elements of life.

Supernovae explosions are so energetic that they synthesize huge amounts of radioactive nickel whose decay into equally large amounts of cobalt and eventually iron powers the output of the supernova in its first few months. Supernovae are the only source we know of even heavier elements that we find around us. The silver, gold and platinum we treasure, serviceable lead, copper, zinc, tin and uranium, all were formed inside massive stars that lived and died before the sun and its retinue of planets appeared. Supernovae are fairly uncommon events, and for a few weeks the exploding star can be as bright as the galaxy it inhabits. None had occurred nearby since the invention of the telescope. All that changed when supernova 1987A was seen to appear in the Large Magellanic Cloud (LMC) in February of that year.

A 12th magnitude blue star, which had been previously studied and catalogued as Sanduleak −69° 202, brightened over 2000 times as news of a catastrophic internal collapse reached its surface and blew it asunder. This event was one of the most important to occur in astronomy for decades, and perhaps the most important ever for the relatively few southern hemisphere telescopes that could see it. Pressure for telescope time everywhere in the southern hemisphere was intense as schedules prepared months before were re-organised and observing strategies were hastily contrived to make the best possible use of what was likely to be a once-in-a-lifetime opportunity.

The picture that appears as **Figure 49** accurately records the colour of the star when the plates were taken in March 1987. By this time, two weeks after the event, the expanding shell of ejecta, containing most of the mass of the blue star, had cooled to a deep yellow. Superimposed in register on the supernova image is a negative picture of the same field, derived from a plate taken in 1984, three years before the supernova appeared. The image of Sanduleak −62° 202 is blended with at least two other, fainter stars in the same line of sight, and in the first days of excitement about the supernova there was some uncertainty about which of these had exploded, but measurements of this plate confirmed the Sanduleak star as the precursor. It was the existence of a set of three of these pre-supernova plates that enabled us to make the light echo image seen in Figure 18.

The expanding shock wave carrying much of the energy from the supernova will travel through the interstellar medium for thousands of years before its force is dissipated. As it does so, its interaction with the tenuous gas between the stars will excite a faint nebula. In the case of the LMC supernova, it will be centuries before we see it, if at all, because of the distance and very crowded star-fields towards what was Sanduleak −62° 202.

A closer, but more ancient supernova provides evidence of this phenomena. A supernova exploded in what is now the constellation of Vela about 10 000 years ago. Its expanding shell is now about 10 degrees across, and very faint. Special image enhancement techniques were needed to reveal the brightest quadrant, seen in **Figure 50.** The energy from exploding stars does more than produce delicate nebulae. The enriched materials they return to the galaxy provide the substance from which new stars and their associated planets will form, and their energy is probably the trigger that disturbs and compresses molecular clouds sufficiently to begin the star-making process. Supernovae are the self-sustaining force that maintains the birth of stars in galaxies.

E. GALAXIES

In all galaxies, star formation seems to occur sporadically wherever the ingredients are available in the right state and subject to an appropriate trigger. This last may be the result of buffeting by supernovae, as suggested above, or the result of encounters with other galaxies. Both these mechanisms seem to be at work in the LMC **(Figure 51).**

This, the nearest of all galaxies is close enough to have been disturbed by the Milky Way's gravitational field; indeed, the LMC may have been captured by our Galaxy and be a satellite of it. In the struggle, the vast bout of star formation in its eastern and northern regions that is seen in Figures 36 and 37 may have been precipitated. It is certainly curious that most of the youngest stars in the otherwise fairly symmetrical galaxy occur in that part of the LMC that is closest to the Milky Way. It is also from here that a huge invisible loop of hydrogen has been detected by radio astronomers, bridging the 50 Kpc between the Milky Way and the LMC, and joining the LMC to its diminutive and rather more distant companion, the Small Magellanic Cloud. Both these galaxies are, for obvious reason, classified as irregulars because they do not easily fall into one of the two main classifications, spirals or ellipticals.

NGC 6822 is also a relatively nearby galaxy, and is a member of a small cluster known as the Local Group to which both Magellanic Clouds and the Milky Way belong. At about 600 Kpc, it is 10 times more distant than the LMC but is still close enough to be resolved into individual stars. At one end of a prominent bar a few clouds of glowing red gas can be seen. As in the LMC, some of these are the wind-blown bubbles so typical of low mass galaxies. At the other end of the bar, bright blueish stars straggle out into what appears to be the beginnings of a spiral arm. The irregular distribution of the bright blue stars of Population I is in contrast to the underlying smooth ellipsoid of much older, faint yellow stars that comprise Population II.

The colours of the two populations of stars in NGC 6822 are easily seen in the colour photograph reproduced as **Figure 52.** It is less than 50 years since the colours of the stars in this galaxy were laboriously measured one at a time by Walter Baade in his effort to establish the existence of different populations of stars.

In **Figure 53,** IC 5152 is also resolved into stars, which means that it is relatively nearby. However despite its proximity, this small galaxy is probably just beyond the Local Group, which is loosely defined as the collection of 30 or so galaxies within 1·5 Mpc of the Milky Way. Apart from the Milky Way and the similarly massive M31 galaxy in Andromeda, most of our immediate extra-galactic neighbours are relatively light-weight collections of stars and gas like IC 5152 and NGC 6822. The bright object which appears at its eastern end is an 8th magnitude blue star in our own Galaxy.

At a distance of about 10 Mpc, the stars of NGC 2997 cannot be resolved by earth-bound telescopes. Like M83, (Figure 3) it is a magnificent spiral galaxy that clearly reveals its internal organisation by its colour. **Figure 54** shows blue spiral arms, peppered with clumps of young stars and the pinkish nebulae from which they came. The arms seem to arise in the yellow nucleus as dust lanes which spiral outwards a considerable distance before fattening out, bloated by newly-formed stars. Like all extra-galactic objects, NGC 2997 is seen through a veil of stars that are in the foreground, and belong to our own galaxy.

Spiral galaxies are quite flat, and NGC 2997 is inclined at about 45 degrees to our line of sight and so appears elongated. NGC 253 is even more strongly inclined to the line of sight, so much so that its spiral structure is scarcely discernable. The closest edge of NGC 253 is uppermost in **Figure 55** and there dust lanes hide the clouds of stars beyond. NGC 253 is one of the dustiest galaxies known, and is rich in the materials that form stars. However, there are very few star-forming regions visible, probably because there is so much dust to obscure them. NGC 253 is one of the nearby Sculptor Group of galaxies and is very close to the south galactic pole, which is why there are so few foreground stars.

Seen from above its pole, NGC 1566 (**Figure 56**) does not seem so different from many other spiral galaxies scattered across the sky, though it is more symmetrical than most. Even the colour diffferentiation between its outer and inner parts is muted. But this is a Seyfert galaxy, an unusual spiral in which there is an unusual amount of activity in the nucleus. This is mainly evident in spectra of the central region, which is more compact and luminous than in most 'normal' spirals. Seyferts, which comprise a few percent of all spiral galaxies, may have black holes at their centres which are responsible for the energetic happenings there.

The diffuse, circular part of NGC 5128 (Centaurus A) consists of thousands of millions of stars and is typical of many giant elliptical galaxies. But Centaurus A is not a typical galaxy. **Figure 57** shows that it is crossed by a dense dust lane which obscures, dims and reddens the light of stars behind it. At the end of the dust lane small patches of younger blue stars can be seen, together with a few pinkish star-forming regions. This is an excellent example of the extra information provided by a colour picture.

The popular name 'Centaurus A' indicates that this most unusual object is the brightest radio source in the constellation of Centaurus. It was one of the first radio sources to be positively identified with an optical object. Apart from radio waves, the galaxy is a copious source of X - and gamma rays as well as infrared and visible radiation. The prominent dust lane and powerful radio radiation are believed to be the remnants of a dusty spiral which was devoured by the more massive giant elliptical galaxy a few billion years ago.

The green- and blue-light plates for this picture were taken in May 1986, shortly after a supernova had been discovered in the galaxy. The red plate was taken the following year, after the 'new' star had faded, which is why one star in the dust lane appears to be an unusual blue-green colour! This is more clearly seen in **Figure 58,** which was made from the same three plates as **Figure 57,** but with a special copying technique that emphasises the small structures while almost eliminating the image of the galaxy itself. This reveals much more detail in the dust lane, especially the pink nebulae and the blue stars they have produced.

Elliptical galaxies do not need dust lanes to make them peculiar. NGC 4486 (Messier 87) in Virgo appears quite normal in **Figure 59**, but, as the strongest radio source in Virgo (*i.e.*, Virgo A) it clearly is not. This is another galaxy believed to have a black hole in its centre. The evidence this time comes in the form of a curious jet emanating from the nucleus. The jet is not seen on this picture, which was made to show some of the huge number of globular clusters in orbit around the galaxy. Virgo A is the most massive member of a rich cluster of galaxies in that constellation.

The enormous cloud of galaxies in Virgo is the nearest moderately rich cluster and its members appear scattered over more than 100 square degrees of sky. The densest region is that centred on the giant elliptical galaxies M84 and M86 which dominate **Figure 60**, though the most numerous of the more than 1000 members of the cluster are the much less conspicuous dwarf ellipticals. A few of these can be seen in this picture as faint fuzzy blobs, just visible above the sky background. Not surprisingly in such a relatively crowded environment, close encounters between cluster members are fairly common and in the upper left (NE) of the photograph NGC 4438 has been distorted by its companion NGC 4435. The whole cluster is receding with an average velocity of over 1000 km per second but there is sufficient variation around that value to suggest that it may be composed of more than one cloud of galaxies which is probably elongated along our line of sight.