Ordinary Meeting, 2005 April 23
held at The English Heritage Lecture Theatre, 23 Savile Row, London W1

Tom Boles, President

Ron Johnson, Nick Hewitt and Nick James, Secretaries

The President opened the sixth meeting of the 115th Session, and invited Dr Nick Hewitt to read the minutes of the previous meeting. These met the approval of members, and were duly signed. Mr Boles then announced that 29 new members were proposed for election; the 50 who had been proposed at the previous meeting were approved by members and declared elected. Mr Nick James, Papers Secretary, announced that two new papers had been approved for Journal publication:

The Priest and the Stuffed Penguin; Father Stephen Perry SJ and the Transit of Venus Expeditions to Kerguelen Island, 1874, and Madagascar, 1882, by Peter Hingley
The Opposition of Mars, 1997, by Richard McKim

Mr Boles announced that the next meeting would be held at the Geological Society on May 25, when the main speaker would be Dr Andy Norton of the Open University, whose talk would be entitled *Outbursts, Orbits and Oscillations*. In the meantime, there would be a meeting of the Comet Section on May 14 at the Institute of Astronomy in Cambridge, and of the Instruments and Imaging Section on May 21 in Northampton.

He then proceeded to introduce the afternoon's first speaker, Dr Omar Almaini, who held a Royal Society Fellowship at the University of Nottingham. His research interests included the interconnection between quasars and galaxy evolution.

Quasars, Black Holes and Galaxy Formation

Dr Almaini opened by outlining the talk to come. First, he would take a historical approach to introduce active galaxies and quasars, before coming to one of the biggest questions raised by them: what power source could fuel such luminous objects? He would then be arguing that super-massive black holes were the only plausible candidate, before asking whether such an object existed in our own galaxy, the Milky Way. Finally, he would air some of his own, more controversial, opinions on the effect of such black holes on the evolution of galaxies.

Setting the scene, he explained that all of the individual stars in the night sky were within the Milky Way, a flat spiral-shaped grouping, 30,000 light-years across, of one hundred billion such stars. Also visible were many other distant galaxies of stars, the nearest example of comparable size being the famous Andromeda Galaxy (M31) – its distance of three million light-years typical of the spacing between galaxies of such size. At the opposite extreme of distance, the speaker showed the famous Hubble Deep Field North (HDF-N), in which more than 1,500 distant galaxies could be seen in an area of sky only one arcminute square.

It was possible to measure the distances to these galaxies, Dr Almaini explained, using Hubble's Law combined with the Doppler Effect. The latter made possible the measurement of galaxies' recessional velocities; it dictated that the observed light from an object moving away from us would be *redshifted* – light it emitted at one wavelength would be observed at a redder wavelength. The magnitude of this redshift was usually measurable: many chemical elements emitted or absorbed light at sharply defined wavelengths, giving rise to readily identifiable features in the spectra of galaxies, and the shifts of the wavelengths of these relative to laboratory measurements yielded the galaxy's redshift.

The usefulness of this arose from the curious phenomenon, first noted by Slipher in the 1920s, that all distant galaxies appeared to be receding from us. More specifically, in 1929, Edwin Hubble had famously discovered a proportionality between their recessional velocities and their distances. Showing Hubble's original data, the speaker commented that the scatter was so great that his confidence in the discovery seemed surprising. Superior modern data had, however, vindicated him, conforming remarkably tightly to his proportionality, now known as *Hubble's Law*. As a result, if the recessional velocity of a galaxy was known, its distance could be estimated by assuming it to follow this pattern.

The observation of distant galaxies provided a wealth of opportunities to study how they had evolved through cosmic history. Many of those in the HDF, the speaker explained, were 8-10 billion light-years distant. On account of the time taken for their light to reach us, we saw them as they had been 8-10 billion years ago, when the Universe had been less than half its present age. By comparing them with nearby counterparts, we could identify changes in the typical properties of galaxies over the intervening time.

Moving on specifically to active galaxies, Dr Almaini recalled that such systems had first been identified by Carl

Seyfert, who had observed in the 1920s that some galaxies, such as NGC 4051, had unusually bright point-like nuclei which could not be resolved, and appeared like stars. With the advent of gamma-ray astronomy in the 1940s, it had become apparent that they also emitted curious spectra, featuring unusually strong fluxes of high-energy photons. It had been speculated that populations of very hot massive young stars (O or B type) in their cores might explain these spectra, but no such model quite matched their shape.

Further mysteries had been unearthed in the 1950s with the birth of radio astronomy – booming at this time largely as a result of the technology and expertise amassed during the Second World War. Many of these "*Seyfert galaxies*" were also found to be radio sources, and many of the more powerful examples were termed "*radio galaxies*". The structuring of this radio emission, as well as its sheer power, was often surprising. For example, Cygnus A, the brightest radio source in the sky, showed two distinct vast bulges of emission. Modern high-resolution radio telescopes showed two narrow jets of material emanating from some central source, feeding each of these lobes.

However, not all radio galaxies could be identified as Seyfert galaxies: others appeared to be associated with point-like objects which looked like stars. All attempts to determine the nature of these stars from their spectra had failed, and they became known as quasi-stellar objects, or "*quasars*" for short. Their spectra exhibited broad emission lines, suggestive of intensely hot gas, but the lines could not be matched to any known elements. It was not until 1963 that Walter Schmitt had realised that the spectral features of quasar 3C 273 would match the redshifted spectrum of a galaxy receding at the tremendous velocity of 48,000 km/s. By Hubble's Law, this suggested that it was not a star at all, rather a very distant and hugely powerful galaxy, with a source at its centre whose luminosity was 1,000 times that of most galaxies. It seemed likely that it masqueraded as a star only because the glare of its bright nucleus completely concealed the nebulosity of the faint surrounding galaxy.

The speaker remarked that this had remained a matter of faith until remarkably recently: nobody had successfully observed a galaxy around a quasar until the advent of the exquisite resolution of the Hubble Space Telescope (HST). This, which was sufficient to allow the intensely bright emission of quasars to be confined to only a small number of pixels, at last allowed the detection of faint nebulosity around them. Many quasars were now known; the most distant as of 2004 had been discovered by the *Sloan Digital Sky Survey* (SDSS) at a redshift of 6.4, or a distance of 12.6 billion light-years. One curious and not yet well understood phenomenon, which became apparent upon the examination of catalogues of observed quasars, was that they appeared to have been much more common when the Universe had been one quarter its present age as compared to the present day: the number of quasars in the Local Universe was much lower than would be expected from the number seen looking back at the distant universe.

Around 10-20% of them were observed to emit highly collimated jets of material, often terminated with the vast lobes of radio-bright material already mentioned. Whilst this also was not well understood, it demonstrated that whatever powered quasars had to be of very substantial mass: to remain stable whilst producing such energetic and focussed beams of material over sufficient time – millions of years – to accumulate the observed radio lobes required a substantial inertia.

However, there was also evidence that their power sources were physically very compact. For example, quasar 3C 279 had been noticed to vary in its B-band (radio) brightness between magnitudes 17 and 12 over a period of years, implying its power source to be no more than a few light-years across – otherwise these variations would be happening on timescales where no information could traverse across it to cause its entirety to vary in synchrony. More recently, X-ray emission from a number of sources, including NGC 4051, had been observed to vary on timescales of hours, implying a power source no larger than the solar system, yet outshining the whole Milky Way, several hundredfold. By the 1960s, many astrophysicists had been asking what the nature of such power sources could be.

No chemical reaction could come close to the energy output required. Even filling the whole solar system with dynamite would not account for the energy emitted by a quasar. Nuclear fusion processes, of the kind which power the Sun, would be more efficient, but these still could not produce enough energy. It was now realised that the release of gravitational energy alone could account for the power achieved by quasars. Dr Almaini explained that the process could be visualised, without reference to relativity, as being rather like dropping an object on Earth. Intuitively, we would expect the object to land on the floor with a bang, emitting energy as heat and sound. This might not be terribly spectacular, but an object dropped from the Earth's orbit onto the Sun would land with a velocity of 620 km/s, and so release rather more energy. If the Sun were compressed down to a diameter of only 10 km – roughly that of a dense neutron star – then the object would strike at one third of the velocity of light. Thus, it could be seen that very dense objects had the potential to release very large amounts of gravitational energy from infalling matter.

The question remained as to whether there existed such compact objects in the Universe. Neutron stars were too faint to observe directly, but the speaker argued that there was compelling evidence for their existence. Historically, the earliest had come in 1968, when Cambridge astronomers Antony Hewish and Jocelyn Bell had stumbled upon a rapidly pulsating radio source in the midst of a supernova remnant in the Vela/Puppis cloud, and soon after, several other similar sources, some pulsating as rapidly as ten times per second. Christened *pulsars*, they were concluded to be rapidly rotating stars, emitting intense radio waves along the directions of their magnetic poles. As stars' magnetic poles were typically not aligned with their rotation axes, this emission would flash in and out of our line of sight as they rotated, rather like that of a lighthouse. But the rotation speeds were phenomenal; any ordinary star would be ripped apart by centrifugal forces if it spun so fast. Only a neutron star could spin ten times per second whilst remaining intact. In subsequent years, some pulsars – termed *millisecond pulsars* – had been found to rotate many hundreds of times per second, only serving to strengthen this conclusion.

The speaker went on, however, to outline evidence that the dense objects at the centres of active galaxies were, in fact, too dense even to be neutron stars, leading to the conclusion that they were *black holes*. Such objects were thought to form in supernova explosions, at the ends of the lives of massive stars – those so massive that they could not form neutron stars without gravity collapsing them still further, down to a single point in space. No force in nature could halt their relentless collapse. Prior to the 1980s, their formation had been conjectured by various gravitational theorists, but observational evidence for their existence had been rather circumstantial. The strongest such evidence had derived from stars which appeared to be orbiting rapidly around partners which were too faint to see, yet which needed to be very massive to account for their partners' orbital speeds. Often vast winds were seen from such stars, apparently being drawn towards their dark companions, often accompanied by weak X-ray emission from the vicinity of the black hole's proposed position, believed to arise from the heating of material as it spiralled inward towards its destiny.

However, Dr Almaini explained that at around this time, observations of active galaxies had also begun to show evidence for bodies too dense to be neutron stars. In M87, for example, spectral observations of the emission from gas within the central nuclear region had revealed emission lines which could be identified as being from known elements, but each had an unexpected profile. It appeared that they were being Doppler shifted towards redder wavelengths on one side of the nucleus, and towards bluer wavelengths on the other. This might be expected if the gas was orbiting around some unseen body at the galaxy's centre, but the orbital velocities, in excess of 100 km/s, required it to be nearly a billion times more massive than the Sun.

The same effect had since been observed in many other active galaxies; perhaps the strongest evidence for a black hole came from NGC 4258, where gas orbiting within half a light-year of the galaxy's centre appeared to be circling some unseen body of 39 million times the Sun's mass. A very tightly bound cluster of neutron stars might *just* be able to account for so much mass in such a small volume, but the formation of such a cluster was difficult to explain. A black hole seemed a considerably more natural explanation.

Having established that there was a weight of evidence for black holes at the cores of other galaxies, considerable attention had turned to investigating whether one might reside at the centre of the Milky Way, Dr Almaini explained. As far back as John Herschel's work, an over-density of globular clusters around Sagittarius had hinted the centre of the Galaxy to lie in this direction, though it was not until Shapley's measurement of the distances of these in the 1920s, illuminating their spherical distribution about a point in that direction, that this could confidently be propounded. In more recent times, a compact bright radio source by the name of Sgr A*, discovered in 1974, was believed to mark the exact spot of the Galactic centre. However, observing this central region was notoriously difficult, owing to the thick clouds of dust which enshrouded its innermost nucleus, concealing it from view in visible light. It was possible to observe it only in the infrared, radio, and X-rays, which passed relatively unhindered through the dust.

Over the past decade, the speaker explained, strong evidence had emerged for the presence of a black hole in this system. It derived from the motions of a cluster of stars known as the *Central Cluster*, localised within a few light-days of Sgr A*. The earliest indications of this cluster's existence dated from 1968, and, with improving instrumentation over subsequent decades, it had now become possible to directly observe its individual stars. In the early 1990s, a dedicated camera, *SHARP*, had been commissioned on the 4-metre *New Technology Telescope* (NTT) at the *European Southern Observatory* (ESO) in La Silla, Chile, with the purpose of monitoring their positions and measuring their velocities. Over the period 1994-2000, a time-lapse movie of their movements had been created, showing them to be orbiting at vast speed around some unseen body close to the position of Sgr A*. From these orbits, the mass distribution in the region could be estimated, but the result proved quite incompatible with any suggestion that the stars themselves might be the dominant masses in the region. Instead, some unseen body, of mass 3.7 million times that of the Sun, contained within a volume comparable to that of the solar system, seemed to dominate.

Describing this as the most remarkable and convincing result that he had seen in his career, Dr Almaini added that it meant that perhaps the most unarguable evidence for the existence of black holes anywhere in the Universe related to one within our own Galaxy.

The speaker closed his talk on a speculative note, outlining his personal, and he admitted slightly controversial, view, that black holes might play a critical role in regulating star formation in galaxies. He presented two pieces of evidence to support this idea. Firstly, he explained that the masses of the central black holes in a number of spiral galaxies had been measured, along with the total mass contained within their central bulge regions – an approximate proxy for the mass of the entire galaxy. The correlation between these masses was found to be remarkably tight. Whilst one might intuitively expect more massive galaxies to host more massive black holes, such tight correlation seemed indicative of some intimate physical connection between the two quantities.

Secondly, he explained that among distant galaxies were observed some very unexpected specimens. Galaxies typically fell into two categories: spiral galaxies, which were actively forming new stars, and elliptical galaxies, which contained no gas from which new stars could form. It was thought that the ellipticals formed from collisions and mergers between spiral systems, and so, among the most distant galaxies – those observed soonest after the Big Bang – few would be expected to be of this type. Yet ellipticals *were* observed, at distances of up to eight-billion light-years. That spiral galaxies could have formed, converted their gas into stars, merged, and then have been flushed of their gas to form an elliptical galaxy, all before this time, was hard to reconcile with pre-existing ideas: the time-scale was simply too short. Specifically, it was thought that the flushing of gas from elliptical systems was driven by blast waves from stars ending their lives in supernova explosions, but the time that this process would take would greatly exceed the time available to form the most distant elliptical systems observed.

The speaker put forward the opinion that these two puzzles had a common solution. The outflows of material from quasars might be responsible for blowing all of the gas out of galaxies at a certain point in their evolution, preventing any further star formation. The first puzzle would be explained because the time available for forming stars might depend upon the mass of the galaxy's central black hole. The second would be explained because the quasar might be able to strip the galaxy of its gas far more rapidly than supernova winds.

Following the applause for Dr Almaini's lively presentation, the President invited questions. Mr Nick James asked whether the stars shown orbiting the Milky Way's central black hole would eventually fall into it, and whether this would end the Galaxy's present period of quiescence. The speaker replied that this was likely: as the stars orbited, viscous drag from surrounding gas would cause them to gradually spiral into the black hole. However, it was difficult to estimate the time-scale over which this would take place, because our knowledge of the density of gas in this region was somewhat limited. In fact, the speaker added that the present quiescence of the black hole was something of a mystery: massive stars invariably produced substantial outflows of gas, and consequently, one might estimate the gas density to be quite high. But in that case one would expect to see it falling into the black hole: it seemed paradoxical that the black hole was quiescent, given the presence of massive stars nearby.

A member asked whether there was any evidence for jets around Sgr A*. The speaker replied that whilst there was radio emission from the region, it did not appear to be collimated into jets. Another member asked what the consequences would be for life on Earth if Sgr A* were to become active. Dr Almaini reassured him that, though spectacular, they would be largely benign: the region might glow as brightly as the Full Moon, but otherwise the activity would be harmless to humanity. Finally, Dr Nick Hewitt said that he recalled that dynamical studies of the Andromeda Galaxy, M31, had suggested it to have a binary black hole at its centre; he asked what this might tell us. Dr Almaini confirmed this recollection, and replied that it might be evidence that M31 had formed from two smaller galaxies. However, the time-scale for the coalescence of black holes after galaxy mergers was uncertain, and so it was difficult to comment further.

Following further applause, the President welcomed Mr Martin Morgan-Taylor, from the Campaign for Dark Skies (CfDS) to give a brief update on a recent development in legislation concerning light pollution.

CfDS Update

Mr Morgan-Taylor reminded members that in 2003 October, a Parliamentary Select Committee had issued a very favourable Report on light-pollution issues, urging that obtrusive lighting become a Statutory Nuisance. He was pleased to announce further progress: the Department for Environmental Foods and Rural Affairs (DEFRA) had responded by modifying its *Clean Neighbourhoods Bill*, which had already been passing through Parliament, adding clauses to this effect. It had received Royal Assent on 2005 April 7. In the past, only Common Law had regulated what lighting could acceptably be installed, which had meant that disputes could be pursued only by Civil Action, i.e. suing, but now prosecution was also possible: any Council Authority approached with a complaint of nuisance lighting was legally obliged to investigate.

However, the speaker cautioned that the interpretation of this new legislation was sure to cause debate. Certain sites, including some of the worst offenders, bus stations and rail depots, were explicitly exempt, deemed to require lighting for safe operation. In addition, the legislation applied specifically to "premises"; the speaker anticipated interesting legal debate on whether streetlamps were such. For domestic premises, however, prosecutions in cases of lights shining onto the property of others would likely succeed.

Mr Morgan-Taylor reported that he and Bob Mizon would be submitting a paper to the Journal as soon as possible, but in the meantime, he would willingly answer any queries received from members. Contact details for the Campaign for Dark Skies could be found inside the back page of the Journal.

Following applause, the President thanked Mr Morgan-Taylor for his work, adding that it was good to see some progress, albeit slow, in the Government's response to this issue. He then welcomed Mr Martin Mobberley to present his latest Sky Notes.

The April Sky

Mr Mobberley opened with an update of the number of UK supernova discoveries, presently standing at 170. Since the previous meeting, Tom Boles had contributed three – one on April 3, and two on April 11 – bringing his tally to 89. He wondered when Mr Boles would reach his one-hundredth discovery, and speculated that based on past performance, he might reach that milestone before the end of September. Those interested in observing supernovae for themselves were recommended to try 2004dj, which, despite having been discovered seven months previously, on 2004 July 31, still remained at mag ~15.7 (as measured on April 10); at a declination of +69°, it was readily UK-observable. Another possibility was 2005ay in NGC 3938 in Ursa Major, discovered by Doug Rich on March 27, which remained an easy CCD target at mag ~15.

In what he believed to be the first mention of a double-star event in the fifteen-year history of his Sky Notes, the speaker next wished to draw members' attention to the forthcoming periastron (close approach) of the two mag-3 stars of Porrima, also known as γ-Vir. 39 light-years away, its components were in a 169-year orbit, with average separation 40 AU – comparable to that of Pluto from the Sun. However, its orbit was of high eccentricity, ~0.9, and at periastron the companions would be very close – based on data from the previous close approach of spring 1836, perhaps less than 4 AU apart, corresponding to 0”3 on the sky. On that previous occasion, the closest half (180° in position angle) of the orbit had been completed in a mere six years, while the remaining 180° had taken 163 years; recent re-analysis indicated that at the moment of closest approach, the rate of change of position angle had been as high as 120°/yr.[1,2] At the time of the forthcoming periastron, around mid-May, it would not be possible to resolve the two stars, but over following months there would be scientific interest in monitoring when the pair first became noticeably elongated, and then distinguishable. In 1836, there had been putative evidence that its rate of change of position angle had continued to rise after periastron, peaking a short while later, in violation of Kepler's Second Law. If correct, this could be explained by the presence of a third unseen mass in the system – Kepler's Laws applying only to two-body systems – opening the possibility for quite unexpected behaviour this time around.

Moving onto novae, the speaker gave an update on Nova Cynus 2005 (V2361 Cygni), although its solar elongation hindered observation at present. Discovered at mag 9.7 on February 10, it was placed at mag 17-18 by the latest observations, Mr Guy Hurst reported. It had dimmed rather rapidly, suggesting that a thick dust cloud might have enshrouded it early in its outburst, and that it might be a DQ Her Type intermediate polar.

The brightest comet in the sky remained Machholz (2004 Q2), fading at mag 8. Having passed close by the celestial north pole in March, it was now heading southward through Ursa Major, and would pass into Canes Venatici on May 18. Looking ahead, the most exciting prospect of coming months would be 9P/Tempel, brightening at mag 11.5, and likely to reach at least mag 9.5 before July 4, when it would be impacted by a 370-kg projectile as a part of NASA's *Deep Impact* mission, whilst situated ~3° north-east of Spica. Throughout July it would remain ~7° above the UK south-western horizon in evening twilight, making it a challenging target at its usual brightness, but were it to brighten significantly after the impact, it might become prominent.

Three fainter comets were briefly mentioned: firstly, 141P/Machholz, at mag ~13, was moving eastward through Taurus, and to pass through northern Orion into Gemini in mid-May. 62P/Tsuchinshan, in Coma Berenices was a little fainter at mag 14. Lastly, the speaker set members a dawn CCD challenge to image 21P/Giacobini-Zinner – comparatively bright at mag 12, but plunging eastward into dawn twilight, and to pass through the Square of Pegasus in mid-May. He asked Jonathan Shanklin whether he knew of any visual observations; he did not, but thought them possible were it not for astronomers' general dislike of early mornings.

Mr Mobberley reported that the oppositions of two bright minor planets were imminent: *Ceres* on May 11 at mag 7 in Libra, and *Pallas* on April 27 at mag 7.2 in Coma Berenices. He then remarked that the time seemed ripe for a detailed look at Jupiter, given its favourable placement, transiting with Virgo at 23h30 BST. Starting with a brief tour of its dark *belts* and lighter coloured *zones*, he showed a schematic of its surface, showing the two most prominent dark bands, the North and South Equatorial Belts (NEB/SEB), straddling the Equatorial Zone (EZ), with the Great Red Spot (GRS) lying on the southern edge of the SEB. Outside this complex lay a myriad of *tropical* and *temperate* belts and zones, many of which were transitory.

In the NEB, the speaker noted a new white spot (WS), first reported by Chris Go on March 12, and a long, dark, blue-tinted, plateau that proceeded it, first reported by Frank Melilo on March 15. In the S.S. Temperate region, the long-lived chain of five anticyclonic white ovals (AWOs) was still evident, presently prograding past the GRS. Cyclonic eddies were often visible between them, and in recent months two had become notably bright: those between A2 and A3, and between A4 and A5.

Turning to the SEB and neighbouring S. Tropical Zone (STZ), it was noted that several SEB jetstream spots had been apparent in February, some of which had entered the Red Spot Hollow (RSH), but which had now become less conspicuous. Two notable dark spots were visible in the STZ; history suggested that they would last 1-2 years before drifting into the RSH. Whilst in that region, Mr Mobberley added that a new S. Tropical Belt had begun to emerge from the proceeding end of the GRS in late March. Moving to the S. Temperate region, the famous Oval

BA remained large and well defined.

To the north, he noted that cyclonic reddish-brown spots (barges) and AWOs (portholes) were appearing in the NEB, as predicted following its 2004 classical expansion event. John Rogers reported that six barges and seven portholes could presently be tracked; all but one were new this apparation, the exception being white spot Z. Further north, there had been a vigorous outbreak of N.N. Temp. B. jetstream spots, joining two long-lived AWOs in the N.N. Temp. Z.; similar spots had previously appeared methane bright, but the speaker noted a lack of methane-band observation of late, urging more.

He added that Damian Peach, perhaps the Association's finest imaging talent, had taken his *Celestron* 9.25" to the clear skies of Barbados, from where he would be returning in mid-May, and so he anticipated a fine display of Jovian images in next month's Sky Notes.

Among the other planets, Saturn remained visible in the evening sky, transiting at 18h30 BST. To continue the theme of objects rarely mentioned in his Sky Notes, the speaker added that Pluto would reach opposition on June 14, close to ξ-Serpens; it would be an easy CCD target. Turning briefly to asteroid occulations, he remarked that three events had been forecast for Europe's skies on the night of April 10/11, but regretted to report that after solid cloud cover, no observations had been reported.

To close, he turned to the hybrid solar eclipse of 2005 April 8, inviting Mr Mike Maunder and Ms Val White to report their observations. Mr Maunder had observed from the decks of a *Discovery* cruise, near Pitcairn Island, where totality had lasted 30 seconds. He reported that he had not been planning any serious photography, but that this had changed when he had met an imaging enthusiast by the name of Miloslav Druckmüller on ship, who had been developing new software to create smooth movies by stacking time-lapsed images. Taking all of the images from those on the cruise, he had created an eclipse movie which, in the speaker's view, had surpassed what the eye could see. He was eager to see what details it might be able to reveal in planetary imaging.

Ms White had travelled on a *Sky & Telescope* expedition to Panama, where the annular phase of the hybrid eclipse had been visible for 14.9 seconds. It was reported that *Bailey's Beads* had been visible almost permanently.

After the applause for Mr Mobberley's presentation, Mr Boles introduced the afternoon's final speaker, Mr Doug Ellison.

Bonneville and Beyond: A Year on Mars with the Spirit Rover

Mr Ellison reported that his title was a little out-of-date: *Spirit*'s exploration of Mars was now in its 463rd sol – Martian days, of length 24 hours and 38 minutes; it had somewhat exceeded its 90-sol design lifetime. He explained that the mission had been shaped by both the successes and the failures before it. In 1996, NASA's successful *Pathfinder* mission had delivered the rover *Sojourner* to the Martian surface, where it had operated for nearly three months. Sojourner had served as a "proof-of-concept" for several new technologies: it was the first time that airbags had been employed to soften the blow of touchdown, and the first time that a rover had driven on Mars. However, problems had also been encountered. The Martian surface had been found to be very dusty, and, when studying rocks, it had been discovered that the ability to abrade them to clear away their dusty top surfaces would have been of great benefit. Pathfinder had been the second mission undertaken under the motto "faster, better, cheaper", though the speaker greeted with mixed reaction the use of its success to promote that strategy's use.

However, the twin failure of NASA's *Mars Polar Lander* and *Mars Climate Orbiter* spacecraft in 1999 had also shaped the *Mars Exploration Rover* mission of which Spirit, aka MER-A, and its twin *Opportunity*, aka MER-B, were two halves. The decision to send two identical rovers, with a short delay between their arrival times, would increase the chances of success. With reference to the "faster, better, cheaper" motto, the speaker thought it only ever possible to achieve two, never all three, and in this case, while the rovers had been designed very quickly, and their longevity was testament to their quality, at $820m, they had not been particularly cheap.

Moving on to discuss the technology employed, Mr Ellison explained that each rover had three communications antennae: two for transmitting directly to the *Deep Space Network* (DSN) of radio receivers on Earth, and one for communicating with NASA's two functioning satellites in Martian orbit, *Mars Global Surveyor* (MGS, 1999) and *Mars Odyssey* (MO, 2001). Communication with the DSN used the rovers' omnidirectional *low-gain antennae*, and steerable, directional, *high-gain antennae*, which could achieve higher data rates. Their *UHF antennae*, for communicating with MGS and MO, were more power efficient, and could achieve a greater data rate of 128 kbit/s, as compared to 3-12 kbit/s for direct communication to Earth. Each satellite was typically visible for 8 minutes each time it passed overhead, in which time 60 Mbit of data could be transferred, subsequently to be relayed on to the Earth. The speaker thought it likely that, in view of the vastly superior power efficiency, future landers would communicate exclusively with satellites.

Mr Ellison went on to describe the rover's cameras, firstly its panoramic camera, "*Pancam*", consisting of two monochrome 1024 × 2048 CCD arrays, each with 16.6° field, mounted on a 1.5 m high mast with a horizontal separation of 30 cm. Each array had a filter wheel that allowed images to be taken in a range of colours, and, in addition, by combining images from both cameras, three-dimensional stereovision could be achieved. The *Pancam Mast Assembly* (PMA) on which the cameras were mounted could be rotated through a full 360° to give a full panoramic view, hence the instrument's name. Spirit's other cameras included two navigation cameras, "*Navcams*", also mounted on the PMA, and four hazard detection cameras, "*Hazcams*", on the body of the rover, each with a 120° field of view. The PMA also housed a mirror which reflected light down its length into an infrared spectrometer, the *Miniature Thermal Emission Spectrometer* (Mini-TES), with which the approximate surface composition of rocks could be estimated remotely, enabling mission controllers to make more educated choices of scientifically interesting targets to study at close range.

Spirit's journey had started on 2003 June 10, launched aboard a conventional Boeing *Delta II* rocket. Its sister had needed additional thrust as a result of taking off later, on July 7, near the close of the launch window, and had been the first customer of Boeing's new *Delta II Heavy* launch vehicle. After a few small trajectory correction manoeuvres along its comparatively straightforward cruise orbit to Mars, Spirit had entered the Martian atmosphere on 2004 January 3, followed by Opportunity on January 25, each housed in protective *aeroshells* consisting of a heat shield and parachute. The frictional deceleration upon entry had peaked at 6 *g* around 3 minutes 45 seconds prior to landing, slowing them from 12,000 mph to 1,000 mph.

When this speed had been reached, 1m43 prior to landing, Spirit's parachutes had opened, and its heat shield detached 20 seconds later. Mars' atmosphere was so thin that a parachute alone could not slow it further than 180 mph – still not a safe landing speed – and so a three-second burn by *Rocket Assisted Descent* (RAD) motors had been required six seconds before touchdown, bringing it finally to a dead halt 10-15 m above the surface. A *Radar Altimeter Unit* on the lander's underside had served to monitor its altitude and control this process, in addition to a camera pointing vertically downwards, the *Descent Image Motion Estimation Subsystem* (DIMES), which had monitored its horizontal motion and controlled the *Transverse Impulse Rocket System* (TIRS) to correct for it. Finally, starting eight seconds prior to touchdown, airbags had inflated around the landing craft to cushion its impact, and, three seconds prior to landing, the payload had been dropped from its aeroshell, bouncing several times before coming to rest. The landing module had then slowly retracted its airbags, and opened to reveal the rover within.

One of the first priorities upon touchdown had been to locate Spirit in satellite images: having an estimated lifetime of only 90 sols, it was necessary to decide upon its scientific targets rapidly. Using all available data, NASA had been able to spot it in detailed MGS images by mid-January; it was found to have touched down 10 km from the centre of its target ellipse – the 82 × 12 km region of the *Gusev Crater* into which it had been aimed.

Meanwhile, attention had been focussed upon dismounting the rover from the lander – a manoeuvre termed *egress*. The rover's first images revealed that the airbags had not retracted so far as had been intended, and all attempts over following days to retract them further failed. Consequently, on January 9, it was decided to rotate Spirit around on the lander and egress by a different route – a contingency operation which had been practiced during its design phase. Finally, on January 15 (sol 12), Spirit rolled forth onto the Martian surface.

Mr Ellison went on to describe how NASA, in somewhat sombre mood, had memorialised several of those whose lives had been lost in its journey of human spaceflight, on January 6 naming the landing site the "*Columbia Memorial Station*", later, a range of three hills to the north the "*Apollo 1 Hills*", and finally, a set of hills to the east the "*Columbia Hills Complex*" – one commemorating each of the crewmembers of *Columbia*'s final flight. These names had been submitted to the IAU for approval.

On January 21, to the immense concern of NASA, Spirit had fallen silent whilst en route to its first scientific target, a rock named by mission controllers "*Adirondack*". On the following day, still no data was returned, though brief transmissions indicated the rover to be in a fault mode. It later became evident that its processor had entered a reset loop, repeatedly rebooting itself after experiencing some fault, running for at most an hour at a time. The culprit appeared to be the rover's static flash memory, or the software which managed it; later it was established that the deletion of now-redundant data from the interplanetary cruise had been overlooked, and the memory was simply full. This data was deleted, and a software patch applied to both rovers to prevent a recurrence. On February 6 (sol 33), Spirit had finally returned to full scientific operations.

Three days were spent analysing Adirondack, first grinding off its dusty surface with the *Rock Abrasion Tool* (RAT), and then undertaking geological analysis of the newly revealed material beneath with a microscopic imager and spectroscope. Mission controllers had then decided to drive towards a nearby crater they named *Bonneville*, around 400 m distant to the north-east. Mr Ellison provided superb illustration of this journey, utilising stereo images from the Pancam, combined with red-green glasses provided to the audience, to provide a 3D view of Mars.

On February 10 (sol 37), Spirit drove 21.2 m, shattering the previous record of 7 m in a sol, set by Sojourner, and by February 17 had driven a total of 108 m, surpassing the total distance traversed by its predecessor. Among various scientific targets along its route was *Laguna Hollow*, a circular depression, where Spirit had spun a small deliberate wheel rut, before spending five sols, 45-49, making a detailed analysis of the soil thrown up. After a few sols dominated by long drives, 30 m setting a new record on sol 51, Spirit had paused to study a rock named *Humphrey* over sols 55-59, grinding three areas of the surface before assessing which minerals were present within, finding evidence that it had once been soaked in water.

Finally, on March 8 (sol 64), Spirit had begun ascending the 15° incline of Bonneville's rim, on the same day surpassing 300 m on its odometer, one of NASA's minimum success criteria for the mission. On the following sol, the opposite rim had come into view and, on the next, a view of the inside of the crater had been gained. Deciding it too dangerous to descend within Bonneville's steep walls, the remainder of the 90-sol mission was spent admiring the newfound scenery and taking soil samples. On March 13 (sol 68), Spirit had even dabbled in astronomy, observing Deimos transit the Sun.

On sol 87, with Spirit still appearing healthy, it had been decided to journey towards the contrasting landscape of the Columbia Hills. On sol 105 it had passed a crater informally named *Missoulla*, not deemed a high-priority target as it seemed comparatively old, and on sol 118 another, *Lahonten*. By sol 125, however, a problem had been becoming apparent with Spirit's front-right wheel: its current draw had increased by a factor of 2-3, and wear on its gearbox lubrication seemed likely. Simple remedies effected no change, and so it was decided that, in order to prolong its life, in case it should be needed later in rough terrain, it should be turned off, and the rover driven in reverse, dragging it behind.

Its journey to the hills had continued, reaching their foot by sol 159, but another issue had started to become apparent by sol 200. Its solar panels were becoming dirty and inefficient, and keeping the rover tilted Sunward had become especially important. The viability of certain routes was affected: a single day spent on a south-faced incline could finish it. A number of rocks had been analysed before powering down for sols 239-262, when solar conjunction had brought an 11-day communication blackout with Earth.

After several months exploring the hills, Spirit's health had recently taken some exciting turns. During the night of sol 419-20 (2005 March 19), its solar panels' energy yield had leapt from an average 350 Watt-hours per sol, 60% of its initial capability, to 600 Wh/sol. Given the weather conditions, it seemed likely that a dust devil had fortuitously swept them clean. In addition, the speaker reported that the rover's defective wheel seemed to be improving, perhaps cured by months of being dragged along. Looking ahead, Spirit seemed as healthy as ever.

To close, the speaker summed up how superbly the rover had surpassed its design lifetime. Over its planned 90-sol mission, it had been expected to drive 600 m, take one full 360° panoramic image, and return 5,000 images. Over the 464 sols that it had been operating so far, it had driven 4,250 m, taken seven panoramic images, and returned 71,706 images. There had barely been time to mention its sister, which had achieved similar, and also continued to operate well. Looking ahead, future missions were not far away: *Mars Reconnaissance Orbiter* (MRO) was scheduled to lift off aboard a Lockheed Martin *Atlas V* launch vehicle on 2005 August 10, and to reach Martian orbit in 2006 March. Looking further ahead, the next planned landing mission was *Phoenix*, scheduled to take off in 2007 August, and to touch down near the icy north pole on 2008 May 25.

Following the applause for Mr Ellison's complete and superbly illustrated account, the President adjourned the meeting until May 25 at the Geological Society.

Dominic Ford

References

[1] Taylor, C., *JBAA*, **155**, 2, 107-8 (2005)
[2] Argyle, R.W., *Porrima: A Close Approach*, in Patrick Moore's *2005 Yearbook of Astronomy*, Macmillan (2004)