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Mount Wilson Observatory
contributions to the study of cosmic abundances of the chemical elements

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This gathering is a centennial celebration of Carnegie Astronomy in Pasadena as well as a stand-alone scientific symposium. My job is to present the celebratory stuff and leave current science to experts, who abound in this audience. I focus my attention on the contributions of the six scientists in Figure 1.1 who, in their own ways, made significant contributions to the investigation of cosmic abundances during their researches at the Mount Wilson Observatory. They serve as archetypes of scientists who worked at Santa Barbara Street in the first half of the 20th century.

George Ellery Hale, our first Director, is hardly representative of a class. He is a class unto himself. I make two observations about Hale's early years at Carnegie.

First, he had to earn his niche. Hale was not simply given the Directorship of a big Carnegie-sponsored observatory in California. In 1904 the final configuration of the Carnegie Institution of Washington was still up for grabs. President Gilman favored NSF-style grants to individuals who would work in Universities. Secretary Charles Walcott, Andrew Carnegie's trusted advisor, envisioned a Carnegie campus with structure like that of his own USGS or NBS. It was in this period, when the Trustees themselves were responding to requests to study, variously, volcanic explosions on Martinique and snake venoms (one of the trustees had been bitten by a snake!), that Hale applied for money to investigate Mount Wilson as a site to pursue his new "astrophysics" (Yochelson 1994). On reading in the Chicago Tribune about Andrew Carnegie's venture into philanthropy, Hale fired off a proposal, and soon discovered that he was in direct competition with "classical" astronomers who were also seeking and receiving Carnegie support, as shown in Table 1.1. Thus, in 1904 Hale's Mount Wilson proposal garnered less than half of the Carnegie allocation for astronomy. However, by 1910 Carnegie's program of individual grants had all but disappeared, three solar telescopes and the 60-inch reflector were operating on Mount Wilson, and Hale had won the battle for Carnegie's astronomy money.

Second, Hale surrounded himself with builders and experimenters, not scholars. In 2003 it is no big deal to execute an ambitious observational abundance program, because there is a high-resolution spectrograph on virtually every major telescope in the world. In contrast there were none in 1903, and Hale set out to rectify that situation. Inspired by the pioneering identifications of chemical elements in the Sun and stars by Kirchoff, Bunsen, and Huggins, Hale set out to put spectrographs at the foci of large telescopes. To accomplish this, he hired engineers, physicists, an optician, and a photographer. The reader may be surprised to learn that during the first five years of operation, Walter Adams was the only astronomer on the

Fig. 1.1. Photographs of six scientists who worked at Santa Barbara Street in the first half of the 20th century.

Mt. Wilson staff, and, as shown in Table 1.2, after a decade there were but three astronomers among a staff of 12.

Hale also recognized that he must understand the spectra emitted by atoms before he could interpret the spectra of stars, and to this end an atomic physicist was among his early appointments.

Arthur Scott King joined Hale in Pasadena in 1909, six years after earning his PhD in physics at UC Berkeley, and five years before Niels Bohr published his quantum theory of the atom. In his dissertation King had investigated how atomic emission lines are affected by the conditions under which they are produced—just what Hale was looking for. King was immediately put to work supervising the construction of a laboratory on Mount Wilson, later moved to Pasadena where there was sufficient commercial power to operate an electric furnace. The core of the laboratory was a 30-foot pit spectrograph, surrounded by the gadgets of atomic spectroscopy.

In this laboratory King undertook a remarkable series of investigations of atomic and

Table 1.1. *Carnegie Grants For Astronomy in 1904*

Investigator	Topic		Award
L. Boss	star position catalog	$	5,000
W. Campbell	star positions, radial velocities	$	4,000
H. Davis	meridian circle data	$	1,500
G. E. Hale	parallaxes with Yerkes 40-inch	$	4,000
S. Newcomb	tests of the law of gravity	$	2,500
W. Reed	variable star observers	$	1,000
H. N. Russell	photographic parallax	$	1,000
G. E. Hale	Mt. Wilson site testing et al.	$	15,000

Table 1.2. *Hale's Mt. Wilson Appointments 1904–1913*

Year	Name	Expertise	From
1904	Walter Adams	Astronomy	Yerkes Obs.
1904	Ferdinand Ellerman	Photography	Yerkes Obs.
1904	Francis Pease	Mechanical Eng.	Yerkes Obs.
1904	George Ritchey	Optics	Yerkes Obs.
1906	Henry Gale	Physics	U. Chicago
1908	Charles St. John	Physics	Oberlin College
1909	Harold Babcock	Electrical Eng.	U. C. Berkeley
1909	Arthur King	Physics	U. C. Berkeley
1909	Frederick Seares	Astronomy	U. Missouri
1912	John Anderson	Physics	Johns Hopkins U.
1912	Adrian van Maanen	Astronomy	U. Utrecht
1913	No appointments	—	—

molecular spectra during the next three decades. He obtained high-resolution spectra, measured accurate wavelengths, and made intensity estimates for lines produced in an electric arc, a spark, between the poles of an electromagnet, and in a furnace that operated at temperatures up to 3000 K. He and his son Robert used absorption tube furnace spectra to calculate relative f-values for lines of Fe I (King & King 1935, 1938). Curious about the quality of their results, I plotted them against the data tabulated by Fuhr, Martin, & Weiss (1988) to obtain Figure 28.2. Considering the checkered history of Fe I f-values, the King data aren't half bad. In the course of these investigations King discovered the doublet structure of the Li I resonance lines (King 1916), and Moore & King (1943) identified the ultimate line of Th II, now used to estimate stellar ages. Analysis of the spectrum the C_2 molecule with Raymond Birge (King & Birge 1930) led to the discovery of a new isotope of carbon, ^{13}C, the abundance of which, relative to ^{12}C, provides important clues about stellar structure and nucleosynthesis in stars. Russell (1935) summed up King's work in his Darwin Lecture thus: "Thirty years of King's assiduous work have resulted in temperature classification, on a uniform basis, for a majority of all the elements, including some of the rarest, such as europium and rhenium. His results have been of inestimable value in the analysis of complex spectra." We all use King's work every time we select atomic lines for abundance analyses. A measure of its importance is that we take it for granted.

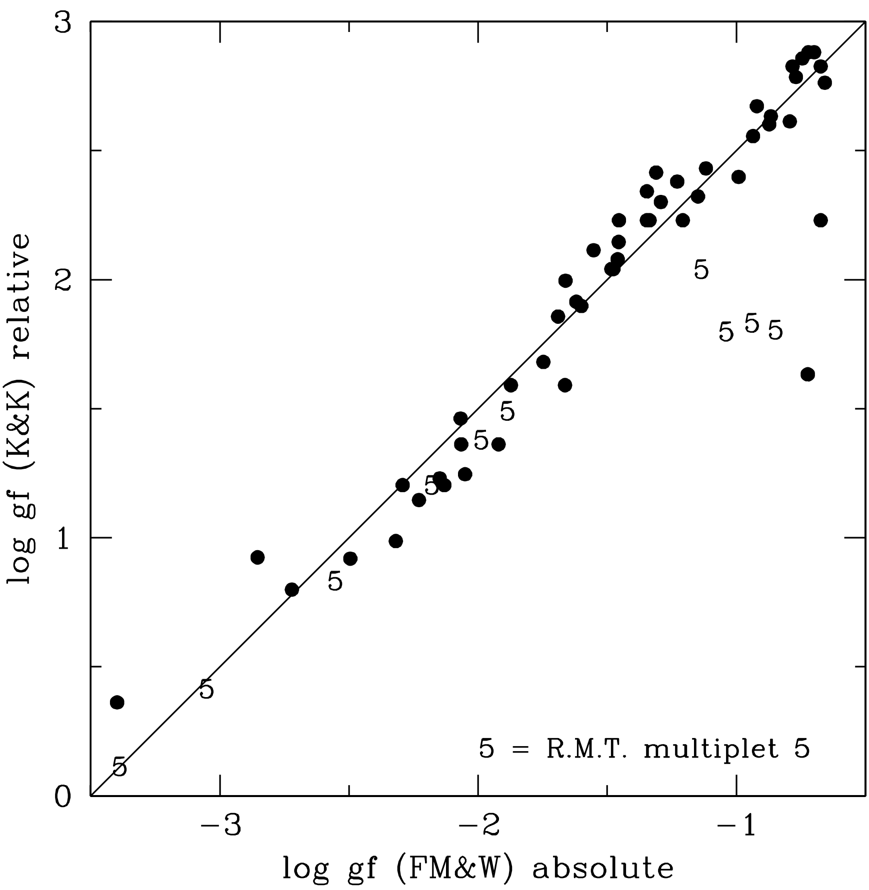

Fig. 1.2. A plot of relative log gf values from King & King (1935, 1938) against absolute log gf values tabulated by Fuhr et al. (1988). The solid line indicates a 1:1 correlation. Note that not all R.M.T. multiplet 5 lines follow the trend.

Henry Norris Russell is my archetype for the Research Associates that Hale and Adams invited to Pasadena to exploit the Mount Wilson/SBS facilities (other examples: Jeans, Kapteyn, Michelson, and Stebbins). Each was offered salary during recurrent leaves of absence from a permanent position elsewhere. Their associations were long-lasting, amounting to decades in most instances.

Russell first came to Pasadena in 1921 and returned for periods of two to three months annually for the next twenty years. Already famous (with Ejnar Hertzsprung) for the diagram that followed from his work on stellar parallaxes, he came to Pasadena hunting for stellar data to test Saha's (1921) new ionization theory that had proven so successful in predicting Annie Cannon's spectral sequence with an apparently universal set of cosmic chemical abundances. The Mount Wilson Observatory possessed three archives that contained such data: (1) a large database of solar spectrum measurements, (2) a growing archive of high-resolution stellar spectra gathered by Adams, Joy, Merrill, and Sanford, and (3) Arthur King's collection of atomic and molecular spectra.

What the Observatory got was an education: at Hale's request Russell gave lectures on atomic physics, and attendance by the Observatory staff was mandatory. What Russell got is now history. Russell began to solve the many puzzles of atomic structure presented by King's data, searching for series amid forests of lines, using King's temperature classes and Harold Babcock's Zeeman patterns to classify levels, and finally deducing electronic configurations and their associated energy-level diagrams. Russell likened these analyses to cross-word puzzles in no fewer than 16 *Scientific American* articles in the 1920's (DeVorkin 2000). He even devoted a portion of his George Darwin Lecture (Russell 1935) to this analogy. In parallel with his atomic analyses Russell, Adams, & Moore (1928) calibrated the Roland intensities of solar lines, and Adams & Russell (1928) outlined procedures for the analysis of stellar spectra. This effort culminated in Russell' s (1929) abundance analysis of the Sun. His results have stood the test of time: the steady decline of abundances with increasing atomic number, the well-known prominence of even atomic numbers over odd, the exceptionally large abundance of iron, and the extreme rarity of very light lithium and beryllium. In 50 papers about the structures of atoms and stellar atmospheres published in *The Astrophysical Journal* and *Physical Review* from 1921 to 1941 Russell had used his association with the staff of the Mount Wilson Observatory to lay the foundations of quantitative spectrum analysis of the stars. During this time Russell & Saunders (1925) devised their LS coupling scheme for atoms with two valence electrons, and the results were published in Hale's *Astrophysical Journal* under a disarming title: *New Regularities in the Spectra of the Alkaline Earths*. The Abstract of this elegant paper is worth a read.

Horace Welcome Babcock, last manager of the Mount Wilson Grating Laboratory, is representative of the Instrumentalists who have provided Carnegie astronomers over the years with the wherewithal to pursue spectroscopic investigations of the stars. One major effort was devoted to the production of diffraction gratings. Under the supervision of John Anderson (1912–1928) and Harold Babcock (1929–1947), two ruling engines were developed. The second of these was finally brought to a state that satisfied the requirements for high-resolution stellar spectroscopy (Babcock & Babcock 1951). In 1948 Horace Babcock assumed responsibility for the grating laboratory and began to generate useful gratings on a routine basis. "Routine" is perhaps an inappropriate descriptor: the sub-basement at Santa Barbara Street is filled with carefully labeled "factory seconds" set aside because of minor flaws. Horace distributed successful ones to 30 institutions around the world (Babcock 1986). Charity begins at home: three interchangeable gratings were installed at the Mount Wilson 100-inch coudé spectrograph, and a mosaic of four were provided for the Palomar 200-inch coudé spectrograph. The competition was not neglected. I recall, as a graduate student at Lick Observatory in 1958, the arrival of Olin Wilson from Pasadena carrying two of Horace's gratings for the newly completed 120-inch coudé spectrograph. George Herbig would later use one of these gratings to conduct his pioneering survey of lithium in G-dwarfs.

Lawrence H. Aller, one of the many distinguished Guest Investigators at Mount Wilson, co-authored a celebrated paper (Chamberlain & Aller 1951) that established convincingly, for the first time, that so-called A-type "subdwarfs" were actually much cooler than A-type stars, and possessed startlingly low abundances of the metals. Curious about the origins of this paper and the reception it received, I visited Aller at his home and talked to Chamberlain by telephone last December.* I learned that circa 1950 Aller spent summers in Pasadena, "doing some observing and hanging around (sic) Santa Barbara Street the rest of the time." Aller didn't make the observations of HD 19445 and HD 140283. Roscoe Sanford, a "nice guy" (Aller's words), gave him the spectra, suggesting that an investigation of these hydrogen deficient (sic) "intermediate white dwarfs" (Adams & Joy 1922) might be rewarding. Aller developed his new ideas about these stars while discussing them in his graduate course at the University of Michigan. He gave the problem to Joseph Chamberlain, a graduate student, who "did all the dirty work" (Aller's words).

Acceptance of their result was neither universal nor immediate. Chamberlain told me that before he read the paper at the Bloomington AAS meeting, Aller warned him "We're gonna catch hell from Jesse (Greenstein)," but, Aller recalled, "Jesse never said a word." So far so good, because Greenstein had become the Local Guru following publication of his famous 1948 paper on the analysis of F-type stars (Greenstein 1948). However, when I asked Aller about reactions he didn't mention Jesse. He just said "Unsold didn't believe it" (Unsold was The Guru of Physik der Sternatmosphaeren to whom all looked for approval). Nor, I might add, did Unsold believe it seven years later in 1958 during a visit to Lick Observatory, when I tried to tell him about the variety of metal-poor RR Lyrae stars I was finding in my thesis study of their K-line strengths. Unsold dismissed my results, patiently reminding me that weak K lines also had been found in metallic line stars and that explanations undoubtedly lay, not in low abundances, but in peculiarities of their reversing layers, perhaps unusual opacities or abnormal temperature structures. And Unsold was not alone. As late as 1962 Otto Struve, still a towering figure in stellar astrophysics, expressed reservations (Struve & Zeebergs 1962) about the concept of chemical evolution that had been discussed at length five years earlier by B^2FH (Burbidge et al 1957). Long-held dogma about universal cosmic abundances died slowly.

Paul Willard Merrill, a Mount Wilson Observatory Staff Member, earns a place in my sextet because of his discovery of purely radioactive technetium in a subset of long-period variable stars (Merrill 1952) we now know to be s-process rich. His discovery provided the first direct evidence for recent nucleosynthesis of heavy elements within a star. The title of Merrill's discovery paper bears his characteristically conservative stamp: *Spectroscopic Observations of Stars of Class S*. He was generally skeptical of theoretical arguments, and preferred a Baconian process of seeking truth through exhaustive observation and measurement. It was his penchant for careful identification that enabled Merrill to recognize feeble technetium lines in the extraordinarily complicated spectra of cool stars.

I cannot resist the temptation to conclude my remarks with a few recollections about my Mount Wilson colleagues that you probably will never hear about from anyone else. For example, you probably will never hear:

(1) That Roscoe Sanford spent most and perhaps all Christmas and/or New Year's days from 1922 through 1931 observing on Mount Wilson. I learned this by accident from his table of radial velocities for U Monocerotis (Sanford 1933).

(2) That Paul Merrill ate a peanut butter sandwich at the Reyn restaurant every weekday during odd-numbered years. In even-numbered years he ate a fried egg sandwich and Alfred Joy ate the peanut butter sandwich. I discovered only the odd-numbered part as an

* I am sorry to report that Lawrence Aller died on March 16, 2003, before I could show him this manuscript.

undergraduate research assistant to Guest Investigator Martin Schwarzschild in 1951. Years later I learned about the even-numbered years from Olin Wilson.

(3) That Paul Merrill firmly believed that 1-N emulsions were best sensitized by soaking them in lemon juice.

(4) That Ira Bowen always inspected change left as tips by his colleagues at the Reyn restaurant with his pocket ocular in search of rare coins. And finally,

(5) That Horace Babcock harrumphed as "inappropriate" Robert Howard's proposal, made during a 1970s Observatories Committee meeting, that Carnegie follow Caltech's lead and refer to itself as Carwash.

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2

Synthesis of the elements in stars: B^2FH and beyond

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2.1 Introduction

Fred Hoyle was the H in the alphabetically listed authors of the long paper (Burbidge et al. 1957) on building the chemical elements through nuclear reactions occurring during the evolution of stars in our Galaxy. But this work had its origin 11 years earlier, in the seminal 40-page paper by Fred Hoyle, which was presented at a meeting of the Royal Astronomical Society in London on November 8, 1946. That paper was entitled "The Synthesis of the Elements from Hydrogen" (Hoyle 1946). I have never forgotten the experience of listening to Fred giving this exciting account of his work on building the elements in the abundance peak around iron, where statistical equilibrium would prevail in high-temperature, high-density interiors of evolved stars.

This was indeed a seminal paper. Work on the composition of the Sun's atmosphere had provided data on the relative abundances of the elements, available before its publication by Hans Suess and Harold Urey (see, e.g., Suess & Urey 1956), and Fred had noticed that there was a peak in the abundances of the elements centered on iron, where he knew the packing fraction, or binding energy per nucleon, reached a maximum, making such elements stable at high temperatures and pressures. Color-magnitude diagrams of stars in various clusters, from the work of Allan Sandage, had given information on the evolutionary tracks of the stars of different masses when they leave the main sequence, so Fred was free to calculate what would happen when stars reached the end of the observed tracks.

Fred Hoyle's 1946 paper came at a time when the current theory was that the elements were created primordially by the coagulation of neutrons just after the birth of the Universe. It was something of a joke that such a process would meet with trouble at masses 5 and 8, there being no stable elements here. Gamow, always ready with diagrams and drawings to illustrate his work, drew pictures of two ditches at masses 5 and 8, with himself jumping over them. George Gamow, Maria Goeppert-Mayer, and Edward Teller were working at that time on this primordial agglomeration of neutrons, in spite of the difficulty at masses 5 and 8.

2.2 Iron-peak Elements and Supernovae

But it was Hoyle who realized the significance of the peak in the abundances of the elements centered on iron, and stretching from nuclear mass number $A \simeq 40$ to $A \simeq 60$, containing the isotopes of elements from Ca to Zn. A modern discussion of what B^2FH named the *e*-process (*e* for equilibrium), is given by Bradley Meyer in the publication by Wallerstein et al. (1997). There is a section entitled "The e-Process and the Iron-Group

Nuclei" by Meyer which gives many references both to the physics involved and to work on supernovae, relating this to the decays of the various isotopes involved in the physics of supernova explosions. Supernovae were the locations described in B^2FH as the sites of the *r*-process. That section, in Meyer's account, referring to the excess abundance of ^{44}Ca found in graphite and silicon carbide grains in primitive meteorites, ends with the words: "In 1957, B^2FH could only have dreamed of having such tangible evidence of element formation in stars!"

2.3 Paul Merrill and Technetium

Actually, we had astrophysical evidence—not "tangible," but very clear-cut—for the location of the *s*-process, in which heavier elements are built from lighter ones by the successive captures of neutrons. We named this the *s*-process, "*s*" for "slow," because after each neutron capture that produces an unstable element, there is time for that element to β-decay before capturing another neutron. The clue for the location of the *s*-process came in a landmark Mt. Wilson 1952 paper by Paul W. Merrill—he identified spectroscopic evidence for the unstable element technetium in certain red giant stars (Merrill 1952), stars of class S. With a half-life of $\sim 10^5$ yr*, technetium obviously had to be produced actually in these red giant stars, and then mixed to the surface. We could therefore see such stars as the astrophysical locations where free neutrons must be produced and made available in an interior region, and, after their capture by Fe-peak elements, the products mixed to the stellar surface.

Stars in the relatively stable phase of stellar evolution along the asymptotic giant branch provide a location for the occurrence of the *s*-process. In B^2FH we had as an analogy the flow of water over a riverbed with deep holes in it. Water flowing along and encountering such holes would accumulate there until the hole was filled, when it would flow on to the next hole. The relevant time scale between neutron captures was $\sim 10^5$ yr. The flux of neutrons was represented by the flow of water, and the holes were represented by nuclei with closed shells, at the "magic numbers" of Maria Goeppert Mayer's shell model of nuclei.

During the work of the four of us, we realized that it would be a good idea to get high-dispersion spectra of a star showing evidence for the occurrence of the *s*-process, and determine the abundances of the elements in this and in a standard star for comparison. Merrill's stars of type S would be good, but we knew from our recent work on abundance determination in stars that the analysis of such cool stars would be a real problem. We knew, however, from work by W. Bidelman, that a class of stars known as Ba II stars, seeming to have an overabundance of the element barium, formed in the *s*-process could provide the evidence we needed.

Looking through the literature, we picked the star HD 46407. Geoff, as a Carnegie Fellow, was entitled to apply for observing time on Mt. Wilson. Women, in those far-off days, were not allowed on Mt. Wilson, but, through the persuasive efforts of Willy Fowler and Allan Sandage, Director Ira S. Bowen gave permission for me to accompany Geoff who was awarded time on both the 60-inch and the 100-inch telescopes, as long as we used our own transportation, lived in the summer cottage—the Kapteyn Cottage—instead of in the dormitory called the Monastery, and brought our own food.

The Table shows the results that Geoff and I published (Burbidge & Burbidge 1957). The

* The longest lived isotope of technetium, ^{98}Tc, has a half-life of 4.2×10^6 yr, whereas the isotope formed in the *s*-process is ^{99}Tc, which has a half-life of 2×10^5 yr.

Table 2.1. *The s-Process Ba II Star HD 46407*†

Element	Atomic Weights, *s*-Isotopes	y'	$\langle\sigma N\rangle y'$
Strontium	86, 87, 88	4.7	381
Yttrium	89	7.8	1326
Zirconium	90, 91, 92, 94	4.9	884
Niobium	93	5.2	832
Molybdenum	95, 96, 97	4.8	343
Barium	134, 136, 138	14.9	281
Lanthanum	139	9.8	647
Cerium	140	10.7	407
Praseodymium	141	28.0	672
Neodymium	142, 143, 144, 145, 146	15.7	443
Tungsten	182, 184	13.0	914

†Burbidge & Burbidge (1957)
σ = neutron capture cross-section
N = solar system abundance
y = observed overabundance
y' = overabundance ratio of isotopes built by *s*-process alone
Within a factor$\sim$2, $\langle\sigma N\rangle y'$ is constant: mean $\langle\sigma N\rangle y'$ = 648

elements listed, strontium to tungsten, are elements with one or more isotopes made in the *s*-process. From our observed overabundance, y, for these elements, we used the emerging calculations from B^{2}FH to calculate y', the observed overabundance of isotopes built by the *s*-process alone. We used recently available neutron capture cross-sections, σ, to calculate the product $\langle\sigma N\rangle y'$, and, despite the fact that the cross-sections were not very accurate (they were substantially improved soon afterwards), the product $\langle\sigma N\rangle y'$ was found to be constant to within a factor $\sim$2.

2.4 Recent Work

With the large telescopes and modern instruments available today, the progress of unraveling the details of nucleosynthesis after stars leave the main sequence is one of the most exciting branches of astrophysics. Stars of very low Fe abundance can now be picked out in the halo of the Galaxy, and the study of *r*-process elements there are giving information on the early stellar population and the seeding of the young Galaxy with the products of early supernovae (e.g., Sneden et al. 1998).

But the *s*-process is also yielding very interesting data on stellar evolution. The astronomers working with the 3.6 m telescope of the European Southern Observatory observed a group of same-temperature CH (carbon rich) evolved stars, and found that the line Pb I λ4057.31 is clearly visible and quite strong in three but absent in one. Pb is the last stable element produced in the slow neutron capture chain of nucleosynthesis (Van Eck et al. 2001). Such observations will surely go hand-in-hand with the theoretical work on the late evolutionary stages of stars, and build our knowledge of the history of the Galaxy.