We had a very productive second year with many significant new results and discoveries. The P.I. was assisted in these studies by three of his graduate students, Jason Collier, Julie Ruppert Dalhed and Laura Davies (now graduated), who were partially supported by the grant and worked on grant-related studies. Reference numbers refer to the "Publications Resulting from the NSF Award."

• We are using both ground-based (Keck, HET) and space-based (Hubble Space Telescope, HST) telescopes to make extensive studies of Galactic halo stars. These stars contain the nucleosynthesis products (from the rapid neutron capture process, *i.e.*, the *r*-process) from the earliest generations of stars – the progenitors of the halo stars. The observed stellar abundance distributions – from the lightest neutron-capture elements, such as Ge, along with some of the heaviest, including Pt – are providing new clues about the earliest Galactic *r*-process nucleosynthesis. These in turn will help to identify the characteristics and nature of the first stars in the Galaxy and the Universe. For example, our observational studies of the ultra-metal-poor star CS 22892–052 have demonstrated that the abundances of the heaviest ($Z \geq 56$) *n*-capture elements are consistent with a scaled solar *r* (but not *s*-)-process pattern (see **Figure 1**, and **#1, & #5**). We have strengthened and extended those findings. Our comprehensive stellar abundance comparisons show this same scaled solar system *r*-process elemental distribution for the heavy neutron-capture elements in a group of several (*r*-process rich) halo stars, not just in CS 22892–052 (see **Figure 2**, and **refs. # 1, 5, & 8**). This agreement strongly suggests that there is one *r*-process site, at least for elements $Z \geq 56$, and these relative elemental (and perhaps isotopic - see **# 3, 5, 15, 17**) *r*-process abundances have not changed over the history of the Galaxy.

• To extend and amplify our studies of individual or small numbers of stars, the P.I. has become part of a collaboration (principally with astronomers at the University of Texas) to study large numbers of metal-poor halo stars. This project, known as CASH (Chemical Abundances of Stars in the Halo), is a comprehensive, multi-year, high-resolution spectroscopic survey of more than 1,000 very metal-poor stars ([Fe/H] < -2.0) discovered during the course of previous medium-resolution spectroscopic searches, but not yet observed at high spectral resolution. **This survey will represent, by over an order of magnitude, the largest such high-resolution effort of metal-poor halo stars ever conducted**, and thus will be one of the "legacy results" to come from the Hobby-Eberly Telescope (HET). Such information is required for an improvement in our understanding of the nature and interplay of the nucleosynthetic processes, and to help in identifying their astrophysical sites in the early Galaxy. We expect that this survey, together with additional higher-resolution, higher S/N spectra of the most interesting subset of the objects identified in this survey, will prove capable of resolving numerous fundamental questions concerning the origin of elements in the first generations of stars. Some preliminary studies have already been made with several stars from this study:

• We present an abundance analysis of three newly discovered stars from the Hamburg/ESO survey for which HET observations have been obtained as part of the CASH project (**# 7, 13**). Light elemental abundances of all three stars agree with those of other metal-poor stars. This means that they likely formed from well-mixed gas. Upper limits on the heavier neutron-capture abundances have not eliminated the possibility that these stars are *r*-process enhanced. However, the measured barium abundances are rather low. This work (**# 7**) was led by one of the P.I.'s students, Laura Davies, who worked on some grant-related studies and has now graduated with a Masters degree.

• We present the first detailed abundance analysis of the metal-poor giant HK-II 17435-00532, as part of the HET CASH project (**# 4, 11, 13, 14**). We find that this metal-poor ([Fe/H] = -2.2) star has an unusually high lithium abundance (log (ϵ) = 2.1), mild carbon and sodium enhancements, as well as enhancement of both *s*-process and *r*-process material. The high Li abundance can be explained by self-enrichment through extra mixing mechanisms that connect the H-burning shell with the outer convective envelope. If so, **HK-II 17435-00532 is the most metal-poor star in which this short-lived phase of Li enrichment has been observed**. The *r*- and *s*-material was not produced in this star but was either present in the gas from which HK-II 17435-00532 formed or was transferred to it from a more massive binary companion. Despite current non-detection of radial velocity variations (over a time span of $\sim$ 180 days), it is possible that HK-II 17435-00532 is in a long-term binary system, similar to other stars with r- and s-enrichment.

• In collaboration with J. E. Lawler's (U. Wisconsin) atomic physics group, we have measured experimental transition probabilities in a number of elements, **including the largest-scale laboratory study of these atomic properties of Sm (# 6)**. (The P.I.'s role has involved abundance determinations and analyses of the stellar data.) Utilizing these new laboratory atomic data for the elements Nd, Ho, Pt, Sm Hf and Er, we have obtained new elemental abundance results in the Sun and a small group of metal-poor halo stars, **dramatically reducing the uncertainties in the stellar abundance determinations** (**see Figure 3 and refs. # 1, 5, 8, 12, 16, 18, 20 and 21**). Most recently, our group obtained new, more precise stellar abundance values for Er, Ce, Pr, Dy, Tm, Yb, Lu and other rare-earth (RE) elements based upon new atomic lab data - we have been literally working our way through the periodic table! Newly revised abundances have been derived for the $r-$process-rich metal-poor giant stars CS 22892-052, BD+17^{o}3248, HD 221170, HD 115444, and CS 31082-001 (**#8, 18, 20 and 21**). For these five stars the average Er/Eu, Ce/Eu, Pr/Eu, Dy/Eu, Yb/Eu and Tm/Eu – in fact all RE/Eu – abundance ratios are all in very good agreement with the solar-system $r-$process ratio (**#20, 21**) – these results culminate years of efforts studying the RE elements. Our studies have further strengthened the finding that $r-$process nucleosynthesis in the early Galaxy, which enriched these metal-poor stars, yielded a very similar pattern to the $r-$process which enriched later stars including the Sun.

To widen the scope of these efforts, new initiatives are now being proposed to extend our studies from the rare earths to the iron-peak elements, with many critical implications for supernova nucleosynthesis. Also as a result of the close collaboration between the diverse members of our group and the increased importance of laboratory astrophysics to these studies, the P.I. has become a member of the Working Group on Laboratory Astrophysics, now part of the American Astronomical Society. The P.I. is taking a leading role in emphasizing the nuclear aspects of lab astrophysics.

• In addition to these elemental studies, we have been expanding our observations, analyses and models to examine isotopic abundances in halo stars. We have derived isotopic fractions of barium (Ba), europium (Eu), samarium (Sm), and neodymium (Nd) in two metal-poor giants with differing neutron-capture nucleosynthetic histories (**# 3, 5, 15 and 17**). These isotopic fractions were measured from new very high resolution (R = 120,000), high signal-to-noise (S/N = 160) spectra obtained with the 2dCoude spectrograph of McDonald Observatory's 2.7 m Smith telescope. Synthetic spectra were generated using recent high-precision laboratory measurements of hyperfine and isotopic subcomponents of several transitions of these elements and matched quantitatively to the observed spectra. We interpret our isotopic fractions by the nucleosynthesis predictions of the stellar model, which models s-process nucleosynthesis in the physical conditions expected in a low-mass, thermally-pulsing star on the AGB, and the classical method, which assumes that s-process nucleosynthesis can be approximated by a steady neutron flux impinging upon Fe-peak seed nuclei. These two approaches predict the relative contributions to the Solar System n-capture abundances from the s- and r-processes and, by extension, the relative contributions of these two processes to material in metal-poor stars. **This study for the first time extends the n-capture origin of multiple rare earths in metal-poor stars from elemental abundances to the isotopic level, strengthening the r-process interpretation for HD 175305 and the s-process interpretation for HD 196944.**

• Recently we have we have obtained abundances of light n-capture elements between Z = 40–50 in several halo stars, including CS 22892-052. The abundances of these elements do not show the same pattern as the heavier n-capture elements (*i.e.*, they deviate from the solid line that matches the abundances of the heavier elements) lending support to suggestions of more than one astrophysical r-process site. (**See Figures 1 and 2 and #1, 2, 5, & 9**). Furthermore, our observational and theoretical studies for the elements Sr-Y-Zr indicate there is a possibility that a (newly discovered) primary process – identified as a lighter element primary process (LEPP) by the P.I. – might be responsible for some fraction of the synthesis of each of these three elements (**refs. # 1, 2, 5, 9**). Our abundance observations of Ge (led by the P.I.) surprisingly indicate that this element's abundance appears to scale with iron in the halo stars, and is independent of the Eu abundances in those stars (see **refs. #1, #5**). A new nuclear process associated with neutrinos in supernovae (the ν-p process) had to be invented to explain our intriguing observations (# **5**).

• A series of detailed theoretical calculations, accompanied by observational comparisons, have been undertaken to study these differences in the heavier and lighter n-capture elements. Our studies will also help in ultimately identifying the (still uncertain) site for the astrophysical r-process. The exact conditions for the supernova high-entropy wind (HEW), as one of the favored sites for the r-process, still cannot be reproduced self-consistently in present hydrodynamic simulations. Therefore, we have performed large-scale network calculations within a parameterized HEW model to constrain the necessary conditions for a full r-process, and to compare our results with recent astronomical observations (**# 2, 9**). A superposition of entropy trajectories results in an excellent reproduction of the overall Solar System isotopic abundances ($N_{r,\odot}$) of the "main" r-process elements beyond Sn. For the lighter r-elements in the Fe-group region, our HEW model supports earlier qualitative ideas about a multiplicity of nucleosynthesis processes. In the HEW scenario, these suggestions are quantified, and the origin of the "missing" abundances to $N_{r,\odot}$ is determined to be a rapid primary charged-particle (α-) process, thus excluding a classical "weak" neutron-capture component. This explains the recent halo-star observations of a non-correlation of Cu - Ge and Sr - Zr with metallicity, [Fe/H], r-process enrichment, [Eu/H], and α-element enrichment, [Sr/H]. Moreover, for the first time a partial correlation with the "main" r-process is identified for Ru and Pd (**# 9**).

We have also been examining abundance trends and chemical evolution changes to understand the nature of early Galactic nucleosynthesis and to help to identify the "first" stars .

• In **refs. #1, 5, and 9**: We discuss the abundance trends for the neutron-capture elements in the halo and the chemical evolution of our Galaxy. We have shown that there is a large star-to-star scatter in the neutron-capture/iron ratios at low metallicities (see **Figure 4**) – which disappears with increasing [Fe/H] – suggesting an early, chemically unmixed and inhomogeneous Galaxy. Our abundance comparisons shown in this Figure demonstrate that Mg, an α-element, does not show the same scatter as the r-process element Eu. This strongly indicates different sites (*i.e.* different masses) for the synthesis of these two types of elements (**refs. #1, and #5**).

• We have made detailed observational and theoretical studies of the differences in r-process and slow neutron capture (i.e., s-) process synthesis contributing to early Galactic nucleosynthesis. Our observations strongly demonstrate a change from the r-process to the s-process at higher metallicities in the Galaxy. We show this behavior employing the ratio of [La/Eu] (rather than the traditional, but less reliable [Ba/Eu]) as a function of metallicity (**refs. #1, #5**).

• Utilizing the radioactive (r-process) elements thorium and uranium, we have made (nucleocosmochronology) age determinations for several of these same old, halo stars, placing constraints on both Galactic and cosmological age estimates. Our calculations yield chronometric age estimates for these metal-poor halo stars on the order of 14 ± 4 Gyr (**refs. # 1, 5, & 10**). We examine the Pb and Th abundances in 13 metal-poor stars whose n-capture material was produced almost exclusively in the r-process. We combine our results with other abundance measurements of heavy elements collected from the literature to form a more complete picture of nucleosynthesis of the heaviest elements produced in the r-process (# **10**). Currently we are obtaining new radioactive and Pb abundance data, and new model calculations are in progress.

Integrated with the studies described above is a small component of ground-based observations of supernovae (SNe). The major questions outlined above involve an understanding of the formation, evolution and age of the heavy elements. Since these elements are formed in evolved stars, with the r-process elements presumably in SNe, an understanding of the late stages of stellar evolution is fundamental to understanding the origin of the heavy elements.

• In an attempt to understand more about the late stages of stellar evolution (*e.g.*, mass-loss rates), the P.I., with his students and collaborators, has been following radio emission from SNe decades after outburst. (The P.I. has now been doing this for several decades as well!) The intensity and duration of this emission is directly related to the mass-loss rate and wind velocity in the red giant phase. Former graduate students Larry Maddox (post doc at UIUC) and Chris Stockdale (Professor Univ. of Marquette) who were both supported by previous NSF grants, have been participating in these grant studies.

• With Maddox and Stockdale VLA radio observations have been made of a number of historical supernovae, SNRs, H II regions, and other point sources (*e.g.*, X-ray binaries, etc.) in a number of nearby galaxies. Our work is providing critical information about the transition region between SNe, which (typically) disappear in the optical within two years, and SNRs, which take hundreds of years to initially form as radio sources. **As a result of our extensive work, we have produced the most comprehensive studies available on the evolution of the radio light curves of decades-old SNe** shown below in Figure 5.

• These studies are ongoing and expanding. For example, we have added additional space-based observations, using the *Chandra* X-ray observatory to supplement our ground-based observational efforts. (The P.I. was part of, and a co-PI on, a very large study of extragalactic SNe.) A comprehensive (long-term) radio and X-ray study of a large number of the point and nuclear sources in several nearby galaxies has been ongoing for a number of years, most recently with observations of the galaxies NGC 3184 and M101 (**ref. #22**, and part of the thesis work of Maddox). Our project studies have resulted in new information about galactic nuclei, including the discovery of massive black holes, and are also providing insight into the nature of some quasars, based upon our VLBA observations (**ref. #23**). We are continuing our studies of SNe and SNRs with new VLA and *Chandra* proposals.

Publications Resulting from the NSF Award :

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2. K. Farouqi, K.-L. Kratz, **J. J. Cowan**, L. I. Mashonkina, B. Pfeiffer, C. Sneden, F.-K. Thielemann and J. W. Truran, "Nucleosynthesis Modes in the High-Entropy-Wind Scenario of Type II Supernovae," in *First Stars III*, ed. B. O'Shea, A. Heger, & T. Abel (New York: AIP) 309 (2008)

3. I. U. Roederer, J. E. Lawler, C. Sneden, **J. J. Cowan**, J. S. Sobeck, and C. A. Pilachowski, "Europium, Samarium, and Neodymium Isotopic Fractions in Metal-Poor Stars," in *First Stars III*, ed. B. O'Shea, A. Heger, & T. Abel (New York: AIP) 172 (2008)

4. I. U. Roederer, A. Frebel, M. D. Shetrone, C. Allende Prieto, J. Rhee, R. Gallino, S. Bisterzo, C. Sneden, T. C. Beers and **J. J. Cowan**, "Hobby-Eberly Telescope *Chemical Abundances of the Stars in the Halo* (CASH) Project: I. The Lithium-, r-, and $s-$Enhanced Metal-Poor Giant II 17435-00532," arXiv:0802.3701, *Astrophys. J.*, **679**, 1549 (2008)

5. C. Sneden, **J. J. Cowan** and R. Gallino, "Neutron-Capture Elements in the Early Galaxy," *Annual Reviews of Astronomy and Astrophysics*, **46**, 241 (2008)

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7. L. A. Davies, A. Frebel, **J. J. Cowan**, C. Allende Prieto, and C. Sneden, "The Hobby-Eberly Telescope Chemical Abundances of Stars in the Halo (CASH) Project III. Abundance Analysis of Three

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15. I. U. Roederer, J. E. Lawler, C. Sneden, **J. J. Cowan**, J. S. Sobeck and C. A. Pilachowski, Europium, Samarium and Neodymium Isotopic Fractions in Metal-Poor Stars," in *New Horizons in Astronomy: Frank N. Bash Symposium 2007, ASP Conference Series Vol. 393*, ed. A. Frebel, J. Maund, J. Shen, & M. H. Siegel (San Francisco: Astronomical Society of the Pacific) 263 (2008)

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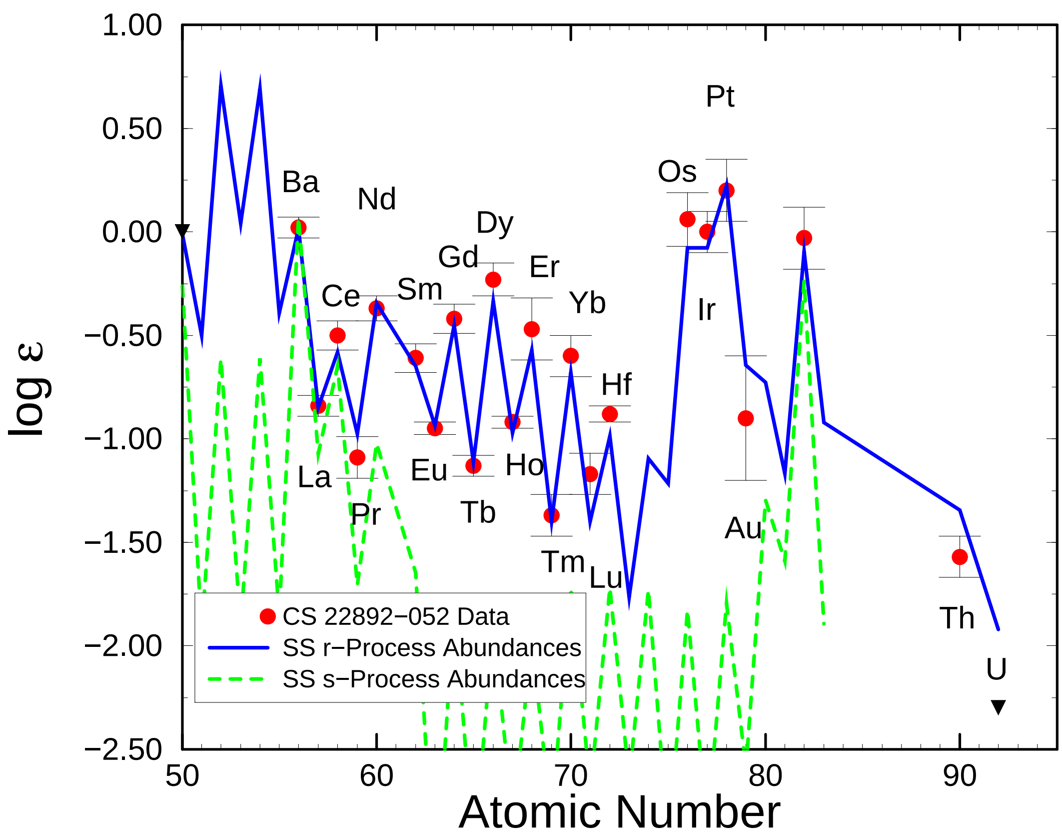

Figure 1. Comparison of CS 22892-052 Z $\geq$ 56 abundances with solar-system *s*- (green dashed line) and *r*-process (solid blue line) only elemental abundance distributions. These curves have been normalized as follows: the *s*-process-only curve (green dashed line) to the CS 22892-052 Ba abundance and the *r*-process only (blue solid line) to the CS 22892-052 Eu abundance. References to the data sources are in (# **5**).

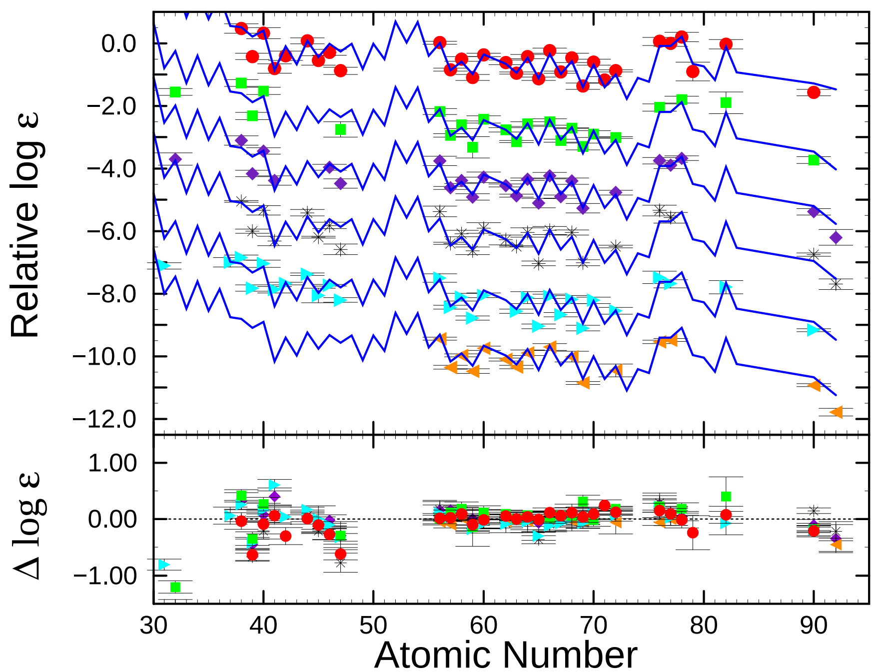

Figure 2. Comparisons of neutron-capture abundances in six *r*-process-rich Galactic halo stars: starting from the top - CS 22892-05222 (circles), HD 115444 (squares), BD+17°324817 (diamonds), CS 31082-001 (stars), HD 221170 (right-facing triangles) and HE 1523-0901 (left-facing triangles). The solid lines are the scaled *r*-process only solar system elemental abundance curves. (From **#5**, see also **#1**.)

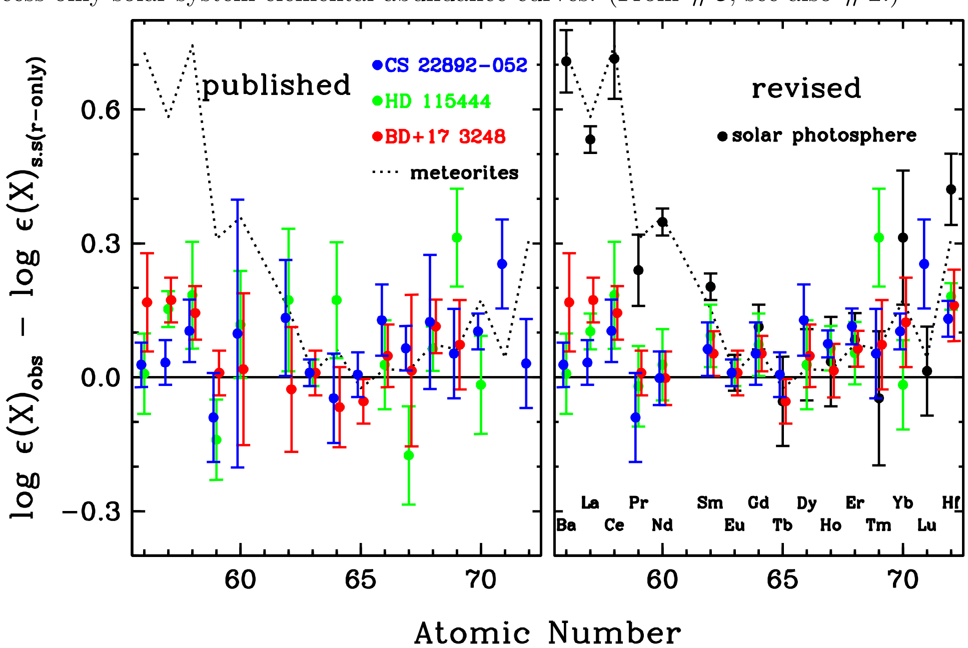

Figure 3. Left-hand panel: abundances of meteorites, CS 22892-05222 , HD 115444 and BD+17°324817 (diamonds) *minus* solar-system *r*-process-only abundances with abundance differences normalized to zero at Eu. Right-hand panel: corrected abundance differences for the three *r*-process rich stars and the solar photosphere after application of recent laboratory (atomic) transition probabilities (**# 1, 5**).

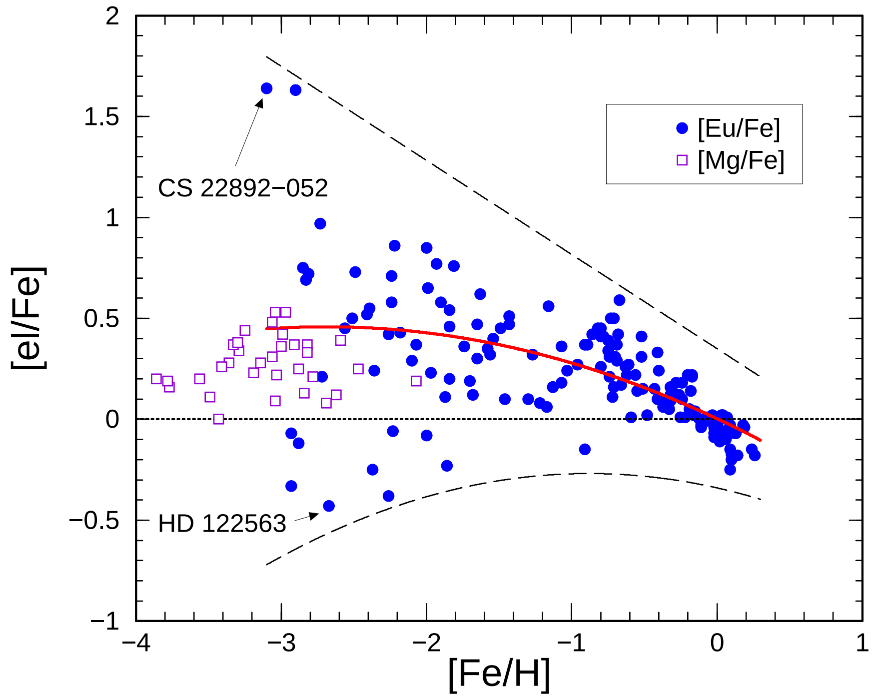

Figure 4. Eu/Fe (filled circles) for a sample of halo and disk stars after Cowan & Thielemann 2004. Representative Mg/Fe data (open squares), for metal-poor stars only, from Cayrel et al. 2004. The solid line is a least-square fit to the Eu data, the dotted line indicates a solar value and the two dashed lines indicate the extent of the Eu/Fe data (**# 1, 5**).

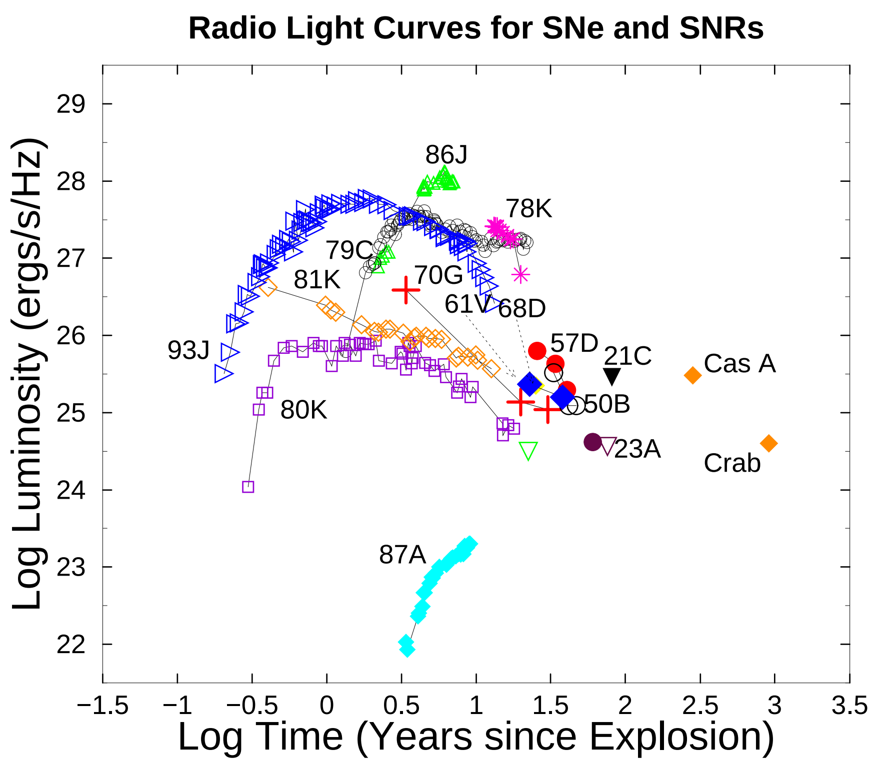

Figure 5. Radio light curve for SN 1970G at 20 cm (indicated by red crosses) compared to several RSNe and SNRs. The SNe data (for 1921C, 1923A, 1950B, 1957D, 1961V and 1970G) have been obtained over decades by the P.I.'s NSF grant-supported observations.