Laboratory Astrophysics: from Observations to Interpretation
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Quantitative atomic spectroscopy, a review of progress in the optical-UV region and future opportunities†

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Abstract. The development of tunable dye lasers and a simple atomic and ionic beam source for all elements were critical in establishing a reliable absolute scale for atomic transition probabilities in the optical to near UV regions. The laboratory astrophysics program at the University of Wisconsin - Madison (UW) concentrates on neutral and singly-ionized species transitions that are observable in astronomical spectra of cool stars, emphasizing the rare earth *n(eutron)*-capture elements and the Fe-group elements that are important inputs to early Galactic nucleosynthesis studies. The UW program is one of several productive efforts on atomic transition probabilities. These programs generally use time-resolved laser-induced-fluorescence (TR-LIF) to accurately measure total decay rates and data from high resolution Fourier transform spectrometers (FTSs) to determine emission branching fractions (BFs). The UW laboratory results almost always are directly linked to astronomical chemical composition efforts. There are good opportunities to extend similar research to other wavelength regions.

Keywords. Stars, Stellar Populations, Stellar Explosions, Nucleo-synthesis, Laboratory Astrophysics, Laser Induced Fluorescence, Fourier Transform Spectrometry.

1. Introduction

Lab astro, specifically improved atoms transition probabilities, is playing a key role in new studies of the Galactic chemical evolution. Elements heavier than the Fe-group elements are made, almost entirely, via n-capture. This is because fusion becomes endothermic beyond Fe where the binding energy per nucleon peaks. Roughly half of the n-capture isotopes are made in the *s(low)*-process and the other half in the *r(apid)*-process. The distinction between the two processes is made by whether or not there is time for beta-decay to occur between the addition of subsequent neutrons. The site of the s-process was unambiguously determined when the unstable element Tc was observed in the spectra of a certain type of red giant (AGB) star Merrill (1952). The site of the r-process, which requires a very much higher density of free neutrons, has been the subject of much discussion and debate for decades. The recent detection and study of a n-star merger event has revealed one promising site of the r-process [e.g. Kasen *et al.* (2017), Abbott *et al.* (2017) and other articles in this Special Issue]. The detection and study of several dozen old or metal-poor (MP) stars with enormously enhanced abundances

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of r-process elements suggests that there may have been a different r-process site early in the evolution of the Galaxy and Universe. Advances in laboratory astrophysics and observational techniques and technologies such as 10 m class ground based telescopes and orbiting telescopes with UV access have been critical in the study of MP stars.

2. Laboratory Astrophysics

Wavelengths of neutral and singly ionized atoms have been known to part per million (ppm) accuracy for some time. The use of large, e.g. 10m class, Rowland circle spectrographs in the first half the 20^{th} Century provided the ppm wavelength data. Although the development of Fourier Transform Spectrometers (FTSs) and laser techniques during the second half of the 20^{th} Century made it possible to further improve wavelength measurements, a more urgent need was for reasonably accurate absolute transition probabilities. Both wavelengths and transition probabilities are essential for quantitative spectroscopy.

The solution to the transition probability challenge was a combination of radiative lifetime measurements from TR-LIF experiments with emission BFs from FTS data (Figure 1). The development at the UW of an atom/ion beam source applicable to essentially all elements of the periodic table provided a significant edge for the UW laboratory astrophysics effort. Although other groups were also productive, the versatility of a sputter source based on a hollow cathode discharge was and continues to be a significant advantage for measurements using TR-LIF on atoms and ions.

Since measured radiative lifetimes establish the absolute scale for atomic transition probabilities, it is essential to understand and control systematic errors. Various tests can easily be used to check for systematic errors from optical depth (vary the atom/ion beam intensity), collisional depopulation (throttle the vacuum pump), and Zeeman quantum beats (zero the B-field to $\sim$1 μTesla in the overlap region of the atom/ion beam and the laser for short radiative lifetimes and use a high, $\sim$3 mTesla, B-field for long radiative lifetimes). The periodic re-measurement of selected benchmark lifetimes in simple spectra such as He I, Be I, Be II, Mg II, etc., which are well known from ab-initio theory, serve as an end-to-end test of the TR-LIF experiment Den Hartog *et al.* (2002).

Emission BFs in complex spectra, such as those of rare earth atoms and ions, represent another challenge. FTS instruments have the resolving power as well as absolute wave number accuracy and precision needed for BF measurements in complex spectra. The UW group has depended heavily on data from the 1 m FTS built by Brault (1976) for the McMath Solar Telescope at Kitt Peak, StateAZ. A relative radiometric calibration or instrument sensitivity is essential for BF measurements. The use of internal Ar I and Ar II branching ratios Whaling *et al.* (1993) as selected and tested by groups in the USA, in Germany, and in Japan has important advantages in controlling systematic errors. A variety of effects from wavelength dependent variations in window transmittance and even time dependent variations due to film growth on a hollow cathode lamp window as well as possible effects from wavelength dependent photon scattering are also incorporated by internal calibrations.

The detailed comparison of independent radiative lifetime and transition probability measurements on lines of Sm II Lawler *et al.* (2008) provides reassurance that systematic uncertainties are under control. The above comparison shows that systematic errors are somewhat easier to control in radiative lifetime measurements than in BF measurements.

3. Abundance determinations for *r*-process elements

Rare earth elements are accessible to ground based astronomy Sneden *et al.* (2009). These elements are thus attractive targets for detailed study of the r-process. Observing time on Hubble Space Telescope is still heavily oversubscribed. Although Figure 2 can

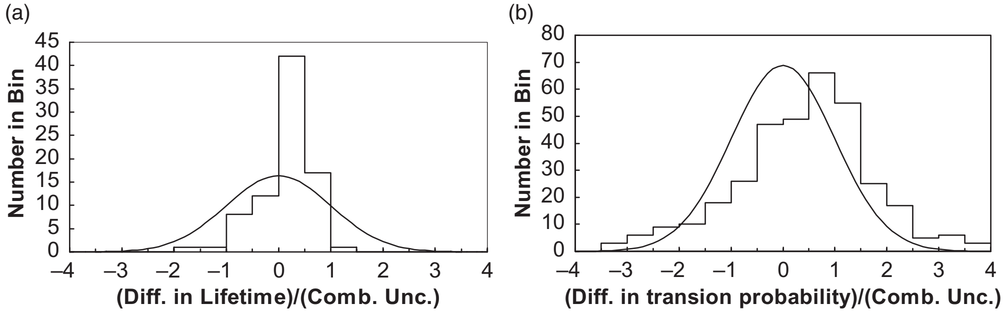

Figure 1. a) Histogram of 82 radiative lifetime differences for upper levels of Sm+ measured independently by the University of Western Ontario (UWO) group minus results of the UW group. b) Histogram of 347 atomic transition probabilities for lines of Sm II measured independently by the UWO group minus results of the UW group. A Gaussian with a standard deviation of unity is superposed on both.

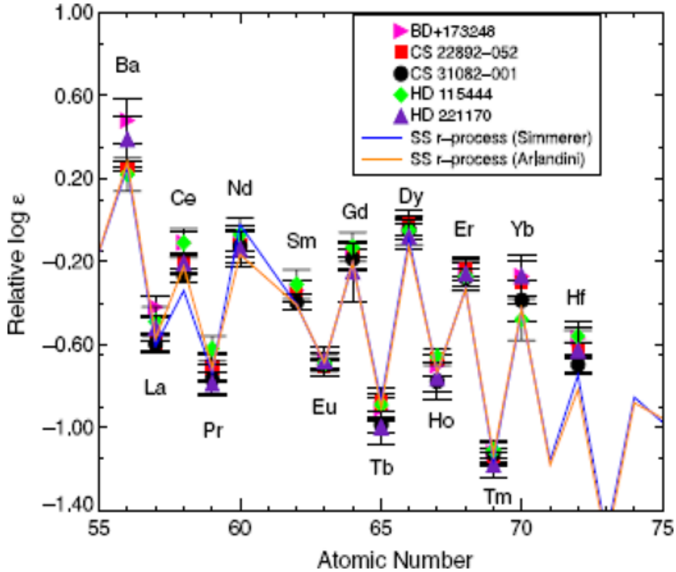

Figure 2. Scaled to Eu relative rare earth abundances for five MP stars. The scaled to Eu relative Solar System abundance from two models Simmerer *et al.* (2004); Arlandin *et al.* (1999) are included.

be interpreted as evidence of a single r-process site, it can also be interpreted as evidence of a consistent pattern from high densities of free neutrons in multiple sites Sneden *et al.* (2016).

The elemental abundance data of Fig. 2 was extracted from stellar spectra using photospheric modeling based on one dimensional and local thermodynamic equilibrium (1D/LTE) approximations Sneden (1973). Although lightly populated high-lying ion levels and nearly any neutral atom level might be out of equilibrium, the ground and low metastable levels of singly ionized species serve as the primary reservoir levels and thus yield reliable abundance values. All of the rare earth data in Fig. 2 is based on strong transitions to reservoir levels of the ion. Furthermore 1D/LTE photospheric models have proven to be applicable to MP stars over a substantial range of parameters Sneden *et al.* (2016) with few exceptions.

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Extension of the lab astro to other wavelength regions is possible. Lasers are well developed in the near IR region and improvements in detectors are possible. X-ray free electron lasers (FELs) with injection seeding will enable line width measurements to provide the same absolute calibration achieved using radiative lifetime measurements. The primary challenge of using X-ray FELs is the current high cost of such facilities, but there are prospects for bringing the cost down.

4. Models for long-duration gamma ray burst and early r-process events

Nearly all MP stars observed thus far seem to contain at least some r-process material. However the oldest MP stars observed to date typically have some non- primordial, heavier than H and He, gas from the ISM when they formed. Statistics on the fraction of true r-process enhanced MP stars may yield deeper insights on the r-process in the early Galaxy. The "R-Process Alliance" [e.g., Sakari *et al.* (2018) and references therein] is systematically observing very metal-poor halo red giant stars to gather the needed statistics on r-process enhancement levels.

Models of Core Collapse (CC) SNe, even for the most massive stars observed today, typically do not yield a robust r-process. The review by Cowan *et al.* (2019) and original source papers Ducan & Thompson (1992); Kramer (2008); Kaspi & Beloborodov (2017); Kasen & Bildsten (2010); Greiner *et al.* (2015); Nicholl *et al.* (2017) indicate that CC SNe from rapidly rotating, magnetized stars can lead to SNe with robust r-process nucleo-synthesis. Magneto Hydro Dynamic (MHD) simulations including relativistic effects Mösta *et al.* (2014) are being used to explore the boundary region in terms of rotation speed and magnetization for a robust r-process.

It is widely thought that Long-Duration Gamma Ray Bursts (LDGRBs) are early CC SNe. Beaming of the gamma rays is necessary to keep energy budgets within reason but hypernovae with total energy budgets in the 10^{52} erg range, or about a decade beyond the 10^{51} erg of normal CC SNe, have been identified. In one case such a Hypernovea was associated with a LDGRB Cowan *et al.* (2019).

Black Hole (BH) formation, which is the outcome of more massive CC-SNe, does not preclude a robust r-process. The accretion disk around a BH is a viable site for a robust r-process [e.g. Pruet *et al.* (2003)]. Collapsar models, which include BH formation and a robust r-process, are appearing.

5. Summary

The oldest MP stars do constrain modeling efforts on the r-process. Accurate, absolute elemental abundances in those stars do reveal details of nucleo-synthesis and the Galactic chemical evolution. Laboratory astrophysics along with observational advances provide improvements in the accuracy of absolute abundance values and in the number of stars that can be studied.

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