Atomic data for astrophysics: Needs and challenges

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1. Introduction

Almost everything we know about the Universe has been discovered through the light that reaches us from the stars, galaxies, nebulae, and other astrophysical objects. The analysis of this light using spectroscopy has yielded information about the size, chemical composition, temperature, and dynamics of astrophysical objects from comets and planetesimals to the Universe. Critical to this analysis has been atomic spectroscopy and the analysis of the wavelengths, energy levels, isotopic and hyperfine structure, and quantities for relevant radiative atomic processes in the plasma. These include oscillator strengths and transition probabilities, cross sections for photoionization, and rates for electron-ion recombination and electron impact excitation. While production of atomic and molecular parameters is rarely under the spotlight of astronomy, very little new research could happen without atomic and molecular data. Atomic and molecular data are as essential to astrophysics as the instruments used to observe spectra,

No field of science places higher demand on the quantity and accuracy of atomic data than astrophysics. For example, the detection of exoplanets requires the wavelength calibration of astronomical spectrographs to a few parts in 10^9. This precision is frequently derived from precisely determined wavelengths from Th-Ar hollow cathode lamps, which have enabled the detection of earth-sized planets causing their stars to wobble by less than 1 ms^{-1} [1,2]. An example of the large quantity of data demanded by astrophysics, the light curve from the neutron star merger detected in August 2017 by LIGO and other space and terrestrial observatories was compared with extensive calculations for atomic structure and processes. The follow up studies established neutron star mergers as a site of the nuclear r(apid)-process for neutron-capture synthesis [3]. Such sites have been long sought because r-process synthesis is known to produce roughly half of all heavy (beyond the Fe-group) isotopes.

All of these applications require extensive atomic reference data that provide comprehensive and accurate wavelengths, energy levels, hyperfine and isotope structure. In general, no existing theoretical framework for atomic structure calculations has attained the accuracy required for detailed spectroscopic analysis for wavelengths, energy levels or transition probabilities of relatively low charge states of complex elements. However, theory provides the large quantity of data that are needed for the measurement of plasma opacities, as well as photoionization and collisional cross sections needed for the analysis of both collisionally ionized and photoionized plasmas. Computations for highly charged ions are significantly more tractable but even here, high quality laboratory data are essential for validation. Only careful laboratory measurements with the appropriate instruments, combined with a critical evaluation of all existing data, can address these needs and accelerate the development of these applications. Critically-evaluated atomic databases are essential for this work.

In addition to atomic data, astrophysics demands similar advances in other areas of atomic, molecular and optical (AMO) physics. These are covered in a companion White Paper [4].

2. Impact of recent progress in Atomic Spectroscopy

The number of groups and scientists working in atomic spectroscopy is small and the numbers have been shrinking for many years. However, significant progress has been made over the past decade in improving the AMO databases for astrophysics. Major analyses in the first two spectra of the elements scandium through copper have been published using high resolution spectroscopy from groups at NIST, the University of Wisconsin-Madison, Imperial College London, UK, and Lund University, Sweden, that have increased the number of classified lines for some elements by factors of three to four and decreased the uncertainties of the line wavelengths by an order of magnitude [5]. The accuracy and quantity of spectral lines with measured transition probabilities for these elements has now increased so that it is possible to use them to distinguish between different stellar atmosphere models and trace the chemical history of the Universe [6].

Oscillator strengths for periodic table groups IVA through VIIA elements have been measured using beam-foil spectroscopy and are among the very few measurements targeting the region below 180 nm observed with the Space Telescope Imaging Spectrograph (STIS) and Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (HST). The lighter elements in these groups, such as Si, P, S, and Cl, give absorption lines in the wavelength region from the interstellar medium (ISM) and circumgalactic medium [7,8]. These can be used to deduce abundances and infer the elemental depletion onto grains in the ISM and estimate the element abundances in damped Lyman-alpha absorption systems in the spectra of quasars and gamma-ray bursts [9,10]. Heavier elements in these groups, such as Ge, Sn, and Pb, are produced by neutron capture [11,12].

New data for the first two spectra of thorium and uranium have provided roughly 30,000 reference lines for the calibration of astronomical spectrographs, providing new calibration data in the IR. This improves the detection of exoplanets around the lower mass M-dwarf stars using the radial velocity (RV) technique [1], as these stars are much brighter in the IR than in the visible. The majority of the exoplanets detected or validated using the RV technique use spectrographs calibrated with either these lamps or molecular iodine absorption cells, both of which rely on benchmark measurements using high-resolution laboratory Fourier transform spectroscopy [2].

The use of 3D, non-LTE modeling techniques for the solar spectrum has resulted in the first homogeneous abundance analysis for the Sun [13] that matches the observations much better than the older semi-empirical Holweger-Müller model. This analysis resulted in lower abundances for many metals, resulting in a discrepancy between the calculated solar opacity and that derived from helioseismology observations [14]. Experiments using the Sandia Z-Facility to create an iron plasma at conditions near the base of the solar convection zone [15], indicate that the solar opacity in this region is too low. The iron ions Fe XVII – Fe XIX are abundant near the boundary of the radiative and convection zones of the Sun and thus the use of earlier data may be responsible for inaccuracies in the plasma opacities [16]. Recent advances in measurement of photoionization cross sections for Ne III [17] show excellent agreement in high resolution resonances with R-matrix calculations. These measurements and calculations are crucial for the solution of the solar plasma opacity and hence to solar photospheric abundances. Since all stars are calibrated with respect to the Sun, this affects the abundances in all stellar systems.

Spectral lines of highly-ionized iron are prominent in EUV and X-ray spectra of stellar coronae. In particular, the bright binary system Capella has been used as an in-flight calibration target and thus is useful for benchmarks studies of atomic data as well [18,19]. Analysis of the line ratios of Fe XVIII and Fe XIX in the accumulated Chandra High Energy Transmission Grating (HETG) Spectrometer shows discrepancies with predicted values up to factors of 2, primarily from inaccuracies in atomic data, presumably dominated by dielectronic recombination and electron impact excitation [20]. Wavelength discrepancies suspected from the spectra of Capella were only partially resolved by experimental data from an electron beam ion trap (EBIT) [21]; highly accurate theoretical calculations now show excellent agreement [22]. The Fe XVII system has been studied extensively since discrepancies with atomic rate data were noted from solar X-ray spectra [23]. Most recent experimental studies using an EBIT still find discrepancies in line ratios as large as 20% [24].

Important work has been done in recent years on inelastic collisional processes (excitation, charge transfer) in stellar atmospheres, which are vital for accurate non-equilibrium (non-LTE) analyses of stellar spectra. In particular, progress on inelastic processes involving electrons and hydrogen atoms on neutral atoms of astrophysical interest has been sorely needed for non-LTE analyses of FGK stars. This has been predominantly provided in recent decades by the development of new theoretical and computational methods. In the case of electron collisions, data are predominantly provided by the R-matrix, B-Spline R-Matrix, and Convergent Close-Coupling methods, driven by groups in the UK, USA and Australia, respectively. For hydrogen atom collisions, full quantum calculations have been done for simple atoms, and based on these results, model approaches developed to provide reasonable estimates for complex atoms. These calculations have been done as part of collaborations between groups with expertise in atomic collisions and quantum chemistry in Sweden, Russia, France and the UK. Additionally, recent decades have also seen substantial progress on spectral line broadening due to electron and hydrogen atom collisions, predominantly due to groups in France, Serbia and Sweden. This work has led to many examples of improved accuracy of stellar spectra, a specific example being the solar oxygen abundance [25], extremely important for understanding solar structure and related to the various problems in opacities mentioned above. For a relatively recent review of the work on collision processes and their astrophysical impact see [26] and references therein.

Measurements of element abundances in galaxies at different redshifts detected in the spectra of background quasars or gamma-ray depend sensitively on the atomic data used, but these data are frequently scattered in the literature and hard for the users to find. A recent compilation of atomic data for resonant absorption lines longward of the H I Lyman limit aims to remedy this [27]. Such data are also required for studies aimed at determining variations in fundamental constants such as the fine-structure constant [28,29].

Analysis of astrophysical spectra requires comprehensive reference data covering all wavelength regions and plasma conditions for atoms, molecules, and the solid state. There are many databases and software packages for data reduction funded and supported by the astronomical community that contain data for specific astrophysical environments and conditions. For example, the AtomDB database [30] focuses on data for X-ray plasma spectral modeling of collisionally-ionized plasmas, the CHIANTI package [31] aims at simulation of extreme ultraviolet spectra, and stellar spectral synthesis remains heavily dependent on the databases and codes of Kurucz [32]. The interpretation of the spectrum of the Perseus cluster from the Hitomi Soft X-ray Spectrometer has been heavily reliant on AtomDB, SPEX and CHIANTI [33]. This enabled the measurement of abundances, the temperature structure, and resonance scattering, quantities that are essential to understand the origin and evolution of galactic clusters [34].

Photoionized astrophysical plasmas are frequently analyzed by the CLOUDY code [35] and the XSTAR photoionization modeling code [36] using associated databases. All of these databases require accurate wavelengths, energy levels and oscillator strengths for atomic spectra before they can begin to provide the spectral modeling required in order to understand the astrophysical spectra. These are provided by critically-evaluated atomic databases, such as the NIST Atomic Spectra Database (ASD) [37]. Many of these databases are now accessible through the Virtual Atomic and Molecular Data Center [38], an interoperable e-infrastructure that provides access to a broad range of atomic and molecular data.

3. Future requirements for atomic data for astrophysics

Analyses of spectra from NASA missions such as the HST, Chandra, the Spitzer Space Telescope, and SOFIA, have depended on advances in laboratory atomic data and are likely to do so in the future. NASA has sponsored several laboratory astrophysics workshops over the past few decades. The most recent of these was in April 2018 and resulted in a report from the Scientific Organizing Committee prioritizing future data needs in laboratory astrophysics [39]. The following section summarizes the findings and expands them to data needs for ground-based astrophysics.

There have been important developments in the past decade on wavelengths, line identifications, and oscillator strengths of neutral through doubly-ionized iron-group spectra. These will continue to be needed in the next decade, particularly in the region below 180 nm, where the majority of experimental oscillator strengths are limited to the lighter elements with $Z<18$. The modeling of stellar spectra from HST spectrographs is reasonably good in the visible and near UV, but in some cases bears little resemblance to the observed spectrum in the far UV due to the lack of these data [5, fig 5]. Atomic data for higher ionization stages of abundant elements are also needed for the interpretation of white dwarf spectra as many of the existing data are old and inaccurate. Accurate wavelengths for these lines are needed in order to test for possible changes in the fine structure constant in a high gravitational field. These will require new measurement techniques to achieve the accuracy needed in the far-UV region where these lines are found [40]. At longer wavelengths, the new generation of extremely large telescopes (>30 m) will have high resolution spectroscopy capabilities that will continue to demand increasing quantity and quality of atomic data. In the IR region, many of the observable atomic lines are fine-structure lines. Wavelengths and collision rates for these lines are needed.

While there has been extensive work recently on the iron-group elements [5,6], progress for heavy elements, with $Z>30$, has been much more limited. This entails expanding the atomic database from 300 ions of 26 elements up to over 5000 ions of roughly 100 elements. Many elements have few experimental transition probabilities, particularly the multiply-ionized rare earth elements and the actinides. These are extremely difficult to calculate due to the complex atomic structure of the ions, but will be needed for the detailed analysis of spectra resulting from neutron star mergers, either directly in the ejecta or in galaxies with abundances enriched by such mergers. Most of the required data for plasma opacities will rely on theoretical calculations due to the huge quantity of data required. Theoretical calculations were essential for the analysis of the initial light curve from the GW170817 merger [3] to detect the production of high-Z elements and are likely to be essential for the future analysis of similar events.

The detection and confirmation of exoplanets using the RV technique requires continuing work on calibration sources. Thorium-argon hollow cathode lamps are used on the majority of high-resolution spectrographs on ground-based telescopes. Newly purchased lamps show contamination with ThO, making them unsuitable for exoplanet detection without additional laboratory characterization [2]. Although optical or infrared (IR) frequency combs may ultimately replace standard lamps, the convenience and low cost of lamps will not be easy to match with a frequency comb. This is particularly the case for new small telescope arrays, such as the MINiature Exoplanet Radial Velocity Array (MINERVA) that are now being used for exoplanet detection and verification using the RV technique [41]. Wavelengths from these spectrographs are calibrated using iodine absorption cells, each of which needs to be calibrated individually. There will be continuing needs for these calibrations in the next decade.

The use of 3D, NLTE modeling of solar and stellar spectra requires extensive calculations of plasma opacities and excitation cross-sections. Extensive close-coupling calculations of Fe XVII have been made in an attempt to resolve the discrepancy between the opacity derived from solar elemental abundances and from helioseismology [16], but it is still not clear whether these calculations can help resolve the observed discrepancies [14,42]. More extensive calculations and confirmation of the *Z*-pinch opacity measurements of Bailey et al. [15] are needed.

Photoionized plasmas, such as H II regions and planetary nebulae, are found throughout the Universe in nearby clouds, star-forming galaxies, the intergalactic medium, and high-redshift quasars. The ionization equilibrium in these regions is determined by ionization processes such as photoionization, collisional ionization and charge transfer, and recombination processes from radiative, dielectronic, three body, and charge transfer recombination. Quantitative analysis of these regions requires millions of cross sections with an accuracy of 15 % [43]. The majority of these data are calculated using high-quality atomic structure calculations, benchmarked with experimental data on a more limited set. At the temperatures typically found in photoionized gases, the electrons populate a limited set of autoionizing levels. The energies of these levels are rarely known, and it is often not clear whether or not the levels are in LTE. Hence, more complete spectroscopy is needed to establish energy levels, especially for these autoionizing levels. This impacts much of observational astronomy because dielectronic recombination affects the ionization of the heavy elements.

High energy plasmas producing X-ray emission are predominantly observed at relatively low spectral resolution (resolving power *R* <~ 50); only the brightest point sources are suitable for observations with the grating spectrometers on Chandra and XMM-Newton. Except for wavelength surveys and the Fe XVII EBIT line ratio measurements noted earlier, there are no experimental benchmarks for most of what we need, and many issues with L-shell iron remain. While the atomic data for the lower *Z* H- and He-like ions appear to be in relatively good shape, for iron and other higher *Z* ions, relativistic effects show unexpected differences from various calculations. The Hitomi microcalorimeter observations of the K-shell region of iron showed numerous issues with atomic data in the existing databases for collisionally ionized plasmas [33]. With Hitomi's unfortunate early demise, additional observations in this region are on hold until the launch of XRISM. Photoionized X-ray plasmas require more complex plasma modeling and thus potentially have more unidentified atomic data issues than for collisionally ionized plasmas. Charge exchange has relatively recently been invoked as a common process in galaxies, as well as in the solar system and at the heliopause; these rates require significant theoretical work, as well as experimental tests [44]. Future spectrometers with higher resolution and collecting area, such as the proposed Arcus explorer [45] and ultimately NASA's large observatory Lynx [46], will require substantial extension and improvement of data on dielectronic recombination rates and wavelengths for less abundant elements in the iron group, such as Cr and Mn [30,47].

Spectroscopic analysis of X-ray spectra presents unique and extreme conditions, with special needs for atomic parameters. An example is found in X-ray binaries, where photoionization and collisional excitation rates are roughly 15 orders of magnitude larger than in H II regions. Electron densities in the accretion disks of X-ray binaries and supermassive black holes may reach densities in excess of ~10^{20} cm^{-3}, compared to densities of 10^3-10^4 cm^{-3} found in H II regions. This presents the need to study high plasma density effects in atomic parameters [48,49]. The radiation field energies can be arbitrarily high in the modeling of X-ray spectra, requiring the inclusion of atomic inner-L and -K shell processes [50,51].

Databases that include critically-evaluated data, as well as databases assembled for specific needs will continue to be essential for the interpretation of astrophysical spectra. Many databases have focused on iron-group elements that have the highest cosmic abundances. However, even for these elements, existing databases are very incomplete in the UV and IR regions. Many of the UV lines from these elements emitted by objects at high redshifts will be shifted into the IR spectral region of JWST. For light elements ($3<Z<10$), many of the wavelengths and energy levels in databases are from compilations from the 1980's. Atomic data for these elements are scattered through the scientific literature and are difficult for users to find. It is important that they be incorporated into major databases, but progress is slow as there are not enough people with the necessary expertise to compile the data. Atomic data for heavier elements will be required for the interpretation of the early light curve of neutron star mergers, which is dominated by multiply ionized heavy elements. Data for some wavelengths and energy levels of the rare earth and actinide elements are covered in Database of Rare Earths at Mons University (DREAM) [52], but many are missing.

4. State of the profession

4.1 Laboratory/Theory

The demands for new and improved atomic data remain strong, with new astronomical spectrographs placing ever increasing requirements on the quality and quantity of the atomic data. However, the number of people active in atomic spectroscopy has been shrinking for many decades. This is reflected in the historical number of publications on atomic spectroscopy. While the number of theoretical papers published over the past 30 years has remained stable at roughly 250 per year, Fig. 1 shows that the number of papers in experimental spectroscopy has been steadily decreasing. While theory has made substantial progress, it remains impossible to calculate parameters such as wavelengths and transition probabilities to the accuracy needed for detailed spectroscopic analysis.

Funding for atomic spectroscopy has also decreased in real terms over the past decade. Past support has come from the NSF Atomic, Molecular, and Optical (AMO) program, but that division has not funded atomic spectroscopy for over 20 years. The same is true for the Department of Energy

(DOE), which stopped funding of atomic spectroscopy several years ago. Support now comes from the NASA Astrophysics Research and Analysis (APRA) and Astrophysics Data Analysis (ADAP) programs, and the NSF Division of Astronomical Sciences (AST). However, Fig. 2 shows that the number of awards made by these programs is small and has decreased from the levels of the early 2000's. Just five groups have been funded by the NSF AST program, with only one in experimental spectroscopy and no groups funded in some years. From 2012 to 2017, NASA funded five groups through the APRA program and two database activities.

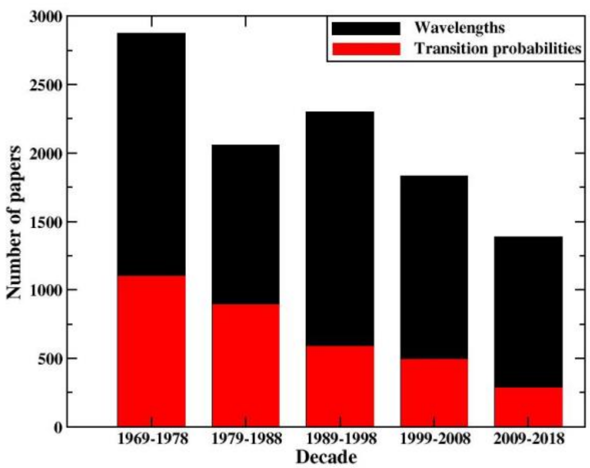

Fig. 1: Number of experimental atomic data papers published per decade [37]

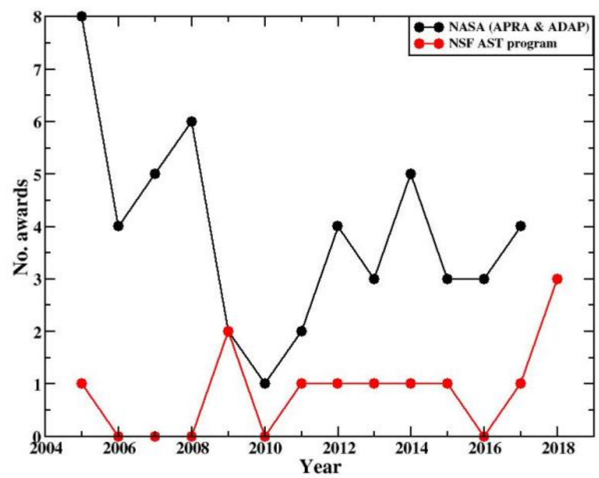

Fig. 2: Number of new awards funded by NSF and NASA

The laboratory astrophysics profession demands expertise in physics and spectroscopy as well as astrophysics. Such a combination of instruction is difficult to find in any university as physics and chemistry departments have moved to specialized low-temperature AMO physics, with very few astronomy departments keeping at least one professorship position in atomic/molecular physics. The few remaining groups in atomic spectroscopy are not sufficient to sustain the field without substantial increases in funding and personnel. Only two universities in the US have students in experimental spectroscopy of the low ionization stages that are in highest demand. In almost all of the groups the principal investigators are within 10 years of retirement and it is not clear where their replacements could come from. The loss of just one person in each of the groups could mean the demise of the laboratory. It would be very hard to re-establish these groups in the future.

There are no groups in the US focusing on atomic data for multiply ionized lanthanides that will be needed for the interpretation of neutron star mergers. The NIST ASD lists just 8 papers in the past decade focused on analysis of these stages, six of which include a group in France now consisting of retirees. Analyses of rare earth elements of interest for multi-messenger astronomy are very complex and can take many years to complete. Young scientists cannot afford to pursue such analyses when their priority is to publish large numbers of papers in order to secure a permanent position. There is thus a danger that existing expertise will be permanently lost.

Electron-impact ionization (EII) and dielectronic recombination (DR) rates in most databases and codes are typically from calculations, but these require experimental validation. For EII, no laboratories remain with operational EII experiments after the decommissioning of the cross beam setup at Oak Ridge National Laboratory. For DR rates, theoretical calculations have shown good agreement with experiments at higher energies but show poor agreement with storage ring measurements at lower energies. Only Germany and China now operate storage rings that can make measurements at these energies and access to facilities in China for US researchers is probably limited.

For spectroscopy of highly-charged ions, in particular, work has largely focused on electron beam ion traps, wherein the combination of novel quantum detectors and the narrow electron-beam energy distribution will open new opportunities to advance our understanding of atomic processes, with high selectivity for excited states and ionized species. However, this selectivity means that transitions between high-excitation levels are not seen in EBITs, but are important for the analysis of white dwarf spectra. In the United States, no permanent scientists are currently performing such measurements on highly-charged ions, and new people must be found to re-establish this work while the few retirees experienced in this field can provide expertise.

The situation is not much better in other countries: The last experimentalist in a once-major group in France has retired, and the pioneering Edlén laboratory in Lund, Sweden, is no longer sustained by full time research scientists. There is uncertainty and pessimism that by the end of the decade there will still be researchers with the necessary expertise to address the high priority needs of the astronomical community.

4.2 Databases/Software development

The maintenance and extension of atomic databases and codes will be critical in the next decades for the interpretation of astrophysical spectra. However, support for many of these databases and codes is currently inadequate for the demands that will be made on them by new survey instruments that will require extensive and complete atomic data for a large number of elements and ionization stages.

NASA and NSF have extensive resources to make the data from major telescopes publicly available, with the result that the papers published on archival data now rival those published on new data in quantity and impact. These resources are not shared by most of the institutions that maintain databases. In contrast, the most widely used atomic databases and codes currently depend on a few individuals, even when they receive NASA/NSF support. They thus may not be maintained after the retirement of the PI. Database activities are not attractive for young researchers near the start of their career, as they are not regarded as sufficiently high-profile work for a faculty position at a university or research institute. Hence there is a danger that support for databases and codes will lapse. Even the Atomic Spectroscopy group at NIST is under pressure. Following an exercise to evaluate the impact of reduced funding, a recent presidential budget includes the phrase: “NIST will also scale back efforts to disseminate, and halt efforts to improve and expand the atomic spectra database that serves a wide range of users.” [53]. Although presidential budget requests are rarely enacted by Congress without change, this phrase illustrates the lower regard for this endeavor as a priority for support.

In addition to atomic databases of published and critically evaluated data, many researchers are in possession of a vast amount of unpublished or partially-published data that is potentially useful in the future. For example, a researcher may take spectra of several stages of ionization of an element or isoelectronic sequence in order to identify spectral lines belonging to just one stage of ionization of one element. Data on the other stages of ionization exist but are useless unless they are placed in a comprehensive and publicly accessible database with appropriate software to analyze them. Research funded by the US government is supposed to be made publicly available, but few researchers have the expertise for this task and such activities are rarely funded. One possible solution would be to create a more central archive of raw or partially-analyzed spectra, similar to those available for the major telescopes, that could be utilized by researchers. An example of what may happen if support for data archives vanishes is the National Solar Observatory Digital archive of data from the McMath-Pierce Fourier transform spectrometer [54]. Data from this instrument have been widely used in publications of atomic spectra and are still a valuable source of high-resolution spectra on many elements. Until a few years ago, this database was searchable with a rudimentary, but still useful, search engine. This has now disappeared, with only FTP access available. Without additional information about the contents of the archive, researchers have to either search through 57 directories of FITS files to find the data they need or download everything and build their own search program.

5. Possible Solutions

The funding of laboratory astrophysics has declined significantly over the past decades, even as the demands on the quality and quantity of laboratory data have increased. The last decadal survey called for an increase of $2 million per year by NASA. While funding for laboratory astrophysics was increased compared to the minimum of FY2010, it has yet to be restored to the levels of the early 2000’s. Current funding levels for new awards in laboratory astrophysics through the APRA program are around $1 million to $1.4 million – similar to the cost to integrate and launch a single 6U CubeSat [55]. A doubling of this could lead to a large impact at a relatively small cost compared to NASA’s missions. This could be done by requiring all major astrophysical projects to include in their budgets a small fraction (~2 %) for laboratory astrophysics. While NSF funding for laboratory astrophysics through the AST program has increased in the last decade, it is still well below the levels seen when this funding came from the NSF-PHY program, discouraging scientists from even applying. Databases remain essential to the astrophysical community but funding of these remains small and is insecure. Both NASA and NSF should increase the current funding for databases.

Increased funding for laboratory astrophysics is, however, useless unless there are people around to apply for the funds and do the work. With the current workforce aging, a concerted effort is needed to attract young scientists and ensure that they have the resources and job stability they need to launch their research career. Dedicated fellowships that are sufficiently generous to catch the eye of university hiring departments are one possible way of attracting new talent, as new faculty positions in AMO physics are currently much more likely to go to candidates from the more lucrative fields such as quantum information. It is important that young scientists know of existing dedicated laboratory astrophysics grant money, are encouraged to apply, and have a reasonable chance of success. Another possibility is the creation of dedicated laboratory astrophysics institutes or networks of facilities through the NSF Physics Frontiers Centers.

One way to extend the existing funding available from NSF and NASA is to leverage international partnerships within the laboratory astrophysics community to share resources, such as facilities and funding. This is particularly important where facilities exist abroad that are not available in the USA, an example being the recently decommissioned TSR heavy ion storage ring in Heidelberg, Germany that has been used for dielectronic recombination measurements.

Better collaboration and communication between astronomers and the laboratory astrophysics community is important to attract and retain young researchers. One possible way of assisting young researchers with this task is with workshops aimed at students and early-career postdocs, an example being the “Cloudy” summer school at the University of Kentucky. With the vast quantities of data that are needed by astrophysics it can be difficult for researchers to decide which problems are most important. It is not uncommon to go to astronomy meetings and ask the question ‘What atomic data do you need’ and get the answer ‘Everything’! This is not helpful either in deciding on a research path or in writing grant proposals and is particularly unhelpful for young researchers at the start of their careers. Due to the lack of awareness of the precarious situation in the field of atomic spectroscopy, many astronomers who review fellowship proposals are disregarding projects aimed at improving atomic data as something which is not a priority, since they believe that someone is already taking care of it. The young researchers applying for these projects are then advised to change their field for something more “fashionable”, but many of the cutting-edge projects in astronomy rely on the not so fashionable task of producing the very accurate data indispensable for the analysis of the very expensively acquired spectra.

6. Conclusions

The measurement, analysis, calculation, and critical compilation of atomic data are vital for many areas from astrophysics. The existing atomic databases remain insufficient for many of these applications. Despite this, atomic spectroscopy has been shrinking over the past decades and is now at the point that there could be no groups left at the end of the next decade unless significant effort is made to recruit and train new people. If the current trends persist, by the time new UV telescopes are launched (e.g. LUVOIR) there will be no people left who know how to calibrate them or measure required data for the interpretation of their spectra. The same may be true for instruments on new large ground-based telescopes currently under construction. What is the purpose of gathering higher spectral resolution observations if the origin of the spectrum is misunderstood and the wavelengths of the lines are not adequately known? The situation could be substantially improved with relatively small investment from the funding agencies leading to a large impact on the community.

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