*Honoring Charlotte Moore Sitterly: Astronomical Spectroscopy in the 21st Century*
*Proceedings IAU Symposium No. 371, 2024*
*D. R. Soderblom & G. Nave, eds.*
doi:10.1017/S1743921323000273

# Accurate new atomic data for Galactic Surveys

**Maria Teresa Belmonte, Pratysuh R. Sen Sarma and Santiago Mar**

Universidad de Valladolid, Departamento de Física Teórica, Atómica y Óptica. Paseo de Belén 7, 47011 Valladolid, Spain
email: mariateresa.belmonte@uva.es

**Abstract.** For the last 20 years, Galactic Surveys have been revolutionizing our vision of the universe and broadening our understanding of the vastness of space that surrounds us. Galactic Surveys such as APOGEE, Gaia-ESO, GALAH, WEAVE and the currently-under-development 4MOST are teaching us a great deal about the chemical composition of stellar atmospheres, the formation and evolution of galaxies and how elements are synthesised in the universe. However, many questions remain unanswered and the current focus of ongoing and future surveys. Answering each of these questions requires the collection of data, normally as spectra, as most of the information we receive from the universe is electromagnetic radiation. Following the very expensive acquisition of astronomical spectra, another crucial task lies ahead: the analysis of these spectra to extract the priceless information they carry. High-quality atomic data of many neutral and ionised species is essential to conduct this analysis.

**Keywords.** atomic data, galactic surveys, transition probabilities

## 1. Introduction

For hundreds of years, humanity has looked out at the universe surrounding us using the instruments available at their time. From the simplicity of the telescope used by Galileo in the early $17^{th}$ century to the sophistication of the recently launched *James Webb Space Telescope*, curiosity has propelled scientists and engineers to create more and more complex instruments. With the advent of bigger and more powerful telescopes, astronomers are able to look further out, reaching objects whose emission was too faint to be observed before. The further out we look into the universe, the further back in time we can see. Due to the development of new and more sensitive telescopes, astronomers are able to do what is known as galactic archaeology and to answer many questions about the origin, structure and evolution of the cosmos.

But not only do we need telescopes to collect the electromagnetic radiation emitted by celestial bodies, but also instruments known as spectrographs to separate this radiation into its different wavelengths. This intensity of radiation versus wavelength, known as a spectrum, is then recorded. These spectra enclose an enormous quantity of information about the bodies that emitted it. They provide details about the chemical elements present and their quantities, allowing us to do studies of chemical composition. The widths and shifts of the spectral lines tell us about the electron densities and temperatures of the plasmas where the radiation was produced and the speeds at which the emitting objects where moving. However, to unlock all this knowledge, we need to use a vast quantity of atomic data: wavelengths and energy levels, transition probabilities, Stark parameters (widths and shifts), hyperfine structure constants, for many different neutral and ionised species.

Despite the very impressive technological improvements in telescopes and spectrographs, studies of chemical composition are being hindered by a lack of high quality experimental atomic data. The quantity and quality of these parameters still lies very far from the astronomers' needs. Experimental spectroscopists still keep in their laboratories the key to unlock the information contained in current and future high-resolution astronomical spectra.

The aim of this contribution is to give a general overview of some of the main ongoing and future Galactic Surveys, speak about some of the current data needs and to give an update about the work we are doing in the Atomic Spectroscopy Laboratory at the University of Valladolid (Spain) to increase the quantity and quality of the atomic data available.

## 2. Galactic Surveys

In their attempt to answer questions about the universe, astronomers have joined efforts and resources. As a result of that, a myriad of what is known as Galactic Surveys has spread around the world. We can find useful definitions of the word *survey* in the dictionary that are a good starting point to describe what a Galactic Survey is. A *geological survey*, for example, is described as "the measuring and recording of the details of an area of land" and for the verb *to survey* we find "to look at or examine all of something, especially carefully". This is exactly what Galactic Surveys do with "something" referring to our universe.

Each Galactic Survey tries to answer a set of specific questions about the cosmos: from chemical abundances to distances and radial velocities, they try to catalogue astronomical objects and their stellar properties. This work is invaluable to perform studies of galactic evolution, variations in the fine-structure constant, search and characterisation of exoplanets, structure of the cosmos or origin of the heavy elements.

From the point of view of people working in laboratory spectroscopy, it is very important to bear in mind and keep updated about the capabilities and needs of the current and future Galactic Surveys. This will guide our choice of the elements to measure in our laboratories to meet the astronomers' atomic data needs.

Galactic Surveys rely on two main players: **telescopes** (which can be space or ground-based) and **spectrographs**. In some cases, the findings of a space telescope or satellite are combined with spectra recorded using a ground-based telescope to reach the satellite or space telescope's full potential. For example, the Gaia-ESO survey analyses data collected by the Gaia satellite (from the European Space Agency, ESA) in conjunction with spectra recorded with the spectrograph FLAMES placed at the *Very Large Telescope* (VLT) at the European Southern Observatory (ESO) in Cerro Paranal (Chile).

Table 1 provides a general overview of some of the main combinations of telescope-spectrograph used by astronomers, indicating the spectral range in which they operate and their resolving power. From the telescopes included in Table 1, we will speak now about two of them due to their current or future importance: the *Very Large Telescope* (VLT) and the *Extremely Large Telescope* (ELT).

### THE VERY LARGE TELESCOPE (VLT)

The *Very Large Telescope* (VLT) is located at 2600 m above sea level in Cerro Paranal (Chile) and started operations in 2006. It is composed of four different unit telescopes (UT1 to UT4) each of them with a primary mirror of 8.2 m in diameter. These four telescopes can be combined to operate as an interferometric instrument known as the VLTI (*Very Large Telescope Interferometer*) (Schöller (2007)). Another important feature

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

**Table 1.** Overview of some of the main combinations of telescope and spectrograph with their spectral coverage and resolving power.

| **Telescope** | | **Spectrograph** | **Spectral range** | **Resolving power** |
|---|---|---|---|---|
| **VLT** | UT2 | GIRAFFE | 370 - 900 nm | ~5 500 - 65 000 |
| | | UVES | 300 - 1100 nm | ~40 000 - 110 000 |
| (The Very Large | UT3 | CRIRES+ | 1 - 5.3$\mu$m | ~ 100 000 |
| Telescope) | ICCF[1] | ESPRESSO | 380 - 788 nm | ~ 70 000, 140 000, 170 000 |
| | | HERMES | 471.8 - 490.3 nm | ~ 28 000, 50 000 |
| Anglo-australian | | | 564.9 - 587.3 nm | |
| telescope | | | 648.1 - 673.9 nm | |
| | | | 759.0 - 789.0 nm | |
| | | WEAVE | 366 - 606 nm | ~ 5000 |
| **WHT** | | | 579 - 959 nm | |
| | | | 404 - 465 nm | ~ 20 000 |
| (William Herschel | | | 473-545 nm | |
| telescope) | | | 595 - 685 nm | |
| **VISTA** | | 4MOST-HRS[2] | 392.6 - 435.5 nm, | ~ 18 000 - 21 000 |
| (Visible and Infrared | | | 516 - 573 nm, | |
| Survey Telescope | | | 610 - 679 nm, | |
| for Astronomy) | | 4MOST-LRS[3] | 390 - 950 nm | ~ 4000 - 7500 |
| | First generation | HARMONI | 470 nm - 2.45 $\mu$m | ~ 3500 (visible) |
| **ELT** | | | | ~ 3500, 7500, 18 000 (NIR) |
| | | METIS | 3-5 $\mu$m | ~ 1500, 100 000 |
| (The Extremely | | MICADO | 800 nm - 2.4 $\mu$m | < 20 000 |
| Large telescope) | | | | |
| | Second generation | ANDES | 400 nm - 1.8 $\mu$m | ~ 100 000 |
| | | MOSAIC | 470 nm - 1.8 $\mu$m | ~ 5000 - 20 000 |

*Notes:*
[1]Incoherent combined Coudé focus
[2]High-resolution spectrograph
[3]Low-resolution spectrograph

is the VLT incoherent combined Coudé focus. In addition to the four UTs, there are other four auxiliary telescopes 1.8 m in diameter which are movable. The VLT works in the spectral range 300 nm to 20 $\mu$m and it is the ground-based telescope with the largest number of publications on its back (second only to the Hubble telescope in the visible range).

Two of the main spectrographs operating at the VLT are:

• **FLAMES (*Fibre Large Array Multi-Element Spectrograph*)**: it is placed in UT2 and composed of two different spectrographs: GIRAFFE and UVES (Pasquini et al. (2002).

(*a*) GIRAFFE: designed to measure spectra of galactic and extragalactic objects, it gets its name from the fact that this spectrograph was placed vertically when it was first designed. It has two diffraction gratings for low and high-resolution, respectively. GIRAFFE covers the spectral range 370 - 900 nm with resolving powers of R ~ 5500 - 65 000 and can observe up to 130 targets simultaneously.

(*b*) UVES (*Ultraviolet visual echelle spectrograph*): it is a cross-dispersed echelle spectrograph covering the range 300 - 1100 nm with an average resolving power of R ~ 40 000. It has two different arms, a blue and a red one, which can achieve maximum resolving powers of R ~ 80 000 and R ~ 110 000, respectively. Unlike GIRAFFE, UVES can look at only 8 objects at a time. When very high radial velocity accuracy is required, an iodine cell can be inserted and used for wavelength calibration.

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

• **ESPRESSO (*Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations*)**: it is located in what is known as the incoherent coudé focus (from the French word meaning "elbow") (Pepe et al. (2021)). It is a high-resolution spectrograph (R ∼ 140 000, 190 000, or 70 000) which collects the light from either a single unit telescope (UT) or the four UTs simultaneously via the so-called UT Coudé trains. It started operating in 2016 and it is the successor of HARPS (*High Accuracy Radial Velocity Planet Searcher*), an echelle spectrogragh used to search for exoplanets using the radial velocity method (Hatzes (2016)). ESPRESSO is able to measure radial velocities with precisions < 10 cm/s (Murphy et al. (2022)).

## EXTREMELY LARGE TELESCOPE (ELT)

The *Extremely Large Telescope* (ELT) is being built in Cerro Armazones in the Atacama desert (Chile) at the European Southern Observatory (ESO). The construction of the ELT started in 2017 and the starting of its operations is planned for 2027. The ELT will have a light gathering surface 256 times bigger than the Hubble Telescope. It will be equipped with two generations of spectrographs. Within the first generation, we find HARMONI (470 nm - 2.45 $\mu$m, R < 18 000), METIS (3 - 5 $\mu$m, R < 100 000) and MICADO (800 nm - 2.4 $\mu$m, R < 20 000). For the second generation, we have ANDES (previously known as HIRES) (400 nm - 1.8 $\mu$m, R ∼ 100 000 and precisions of at least 1 m/s) and MOSAIC (470 nm - 1.8 $\mu$m, R ∼ 5000 - 20 000). The ELT will measure radial velocities with an accuracy of at least 4 m/s. This requires to calibrate the position of measured spectral lines with an accuracy of 1.3 parts in $10^8$ ($3 \cdot 10^{-5}$ nm at 200 nm). To obtain this accuracy, new calibration standards need to be developed as current measurements with fourier transform spectroscopy can only achieve an accuracy of 1 part in $10^7$ due to the uncertainty of the lines used as wavelength standards. The use of laser frequency combs (Araujo-Hauck et al. (2007), Picqué, & Hänsch (2019)) for wavelength calibration is currently under study as it can achieve the required accuracies.

Once we have a clearer idea of the main telescopes available and how they work together with a particular spectrograph, it is easier to get a general view of the main Galactic Surveys. The following is not a complete list, but it attempts to summarize the main characteristics of some of the biggest ongoing and future Galactic Surveys. The products of Galactic Surveys tend to be made public into what is known as data releases. For example, even if measurements with Gaia-ESO finished in 2019, its last data release (DR5.0) happened on 20 May 2022.

## APOGEE (Apache Point Observatory Galactic Evolution Experiment)

The APOGEE survey was one of the SDSS III and IV (The Sloan Digital Sky Survey's third and fourth generations) surveys operating between 2008-2014 as APOGEE-1 and between 2014-2020 as APOGEE-2 (Majewski et al. (2017)). Spectra were recorded using the 2.5 m Sloan Foundation Telescope at the Apache Point Observatory (Texas, USA) and the Irénée du Pont Telescope in Las Campanas (Chile). It provided high- resolution spectra in the infrared (1.51 - 1.7 $\mu$m) with a resolving power of R ∼ 22500 (10 times higher that the SDSS optical spectra). Its objectives were the measurement of radial velocities, chemical abundances and other physical properties of stars.

## **Gaia-ESO**

The Gaia-ESO survey is a large public spectroscopic survey targeting more than 114 000 stars that provides radial velocities, stellar parameters and abundances (Gilmore et al. (2012)). It combines astrometry data from the Gaia satellite (ESA) with spectra

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

recorded at the *Very Large Telescope* (VLT) using the FLAMES spectrograph (300 - 1100 nm, resolving power up to ∼ 110 000). This galactic survey was the first dedicated stellar one that used a 8-m class telescope (Gilmore et al. (2022)).

GALAH (GALactic Archaelogy with HERMES)

The aim of the galactic survey GALAH is to study the formation and evolution of the Milky Way. GALAH is a galactic survey that combines the 3.9 m anglo-australian telescope located in Siding Spring Observatory in New South Wales (Australia) with the spectrograph HERMES (*High efficiency and high-resolution mercator echelle spectrograph*). HERMES covers the spectral regions 471.8 - 490.3 nm, 564.9 - 587.3 nm, 648.1 - 673.9 nm and 759 - 789 nm with resolving powers of R ∼ 28 000 and 50 000.

WEAVE (WHT Enhanced Area Velocity Explorer)

The galactic survey WEAVE (starting 2022) is based at the William Herschel Telescope (WHT) in the Canary Islands (Spain) (Dalton (2016)). The name WEAVE is used both to name the survey and the spectrograph that has recently been mounted at the prime focus of the WHT. WEAVE is a multi-object fibre-fed spectrograph with two arms, one for blue and one for red. It has a low-resolution mode with R ∼ 5000 (radial velocities of 60 km/s) and a high-resolution mode with R ∼ 20 000 (15 km/s). The spectral ranges covered are 366 - 959 nm for low-resolution and 404 - 465 nm, 473 - 545 nm and 595 - 685 nm for high-resolution.

4MOST (4-metre Multi-Object Spectroscopic Telescope)

The survey facility 4MOST will be mounted on the VISTA telescope (ESO Paranal Observatory, Chile). It is currently on its manufacturing phase and is expected to start working in 2024. 4MOST is a wide-field, fibre-fed instrument with 2436 fibres which feed one high-resolution and two low-resolution spectrographs (de Jong et al. (2019)). The high-resolution spectrograph (HRS) will cover the ranges 392.6 - 435.5 nm, 516 - 573 nm and 610 -679 nm at a resolving power R > 18 000. The two low-resolution spectrographs (LRS) will cover the region 390 - 950 nm with a resolving power R > 4000. For wavelength calibration, it will use a Fabry-Pérot etalon with a laser driven light source (LDLS). 4MOST includes not only the instrument, but also other facilities such as data reduction and validation (Table 2).

## 3. Atomic Data Needs

Over the last 20 years, different groups across the globe have worked to increase the quantity and quality of atomic data (wavelengths, energy levels, transition probabilities, hyperfine structure constants, etc.) for the iron-group elements (see Fig. 1). These elements are very important for astronomers due to their high abundance in the universe. The FERRUM project, started in 2000, is a good example of this effort (Johansson et al. (2002)). Extensive analysis performed with Fourier transform spectrometers have provided wavelengths and energy levels with accuracies of 1 part in $10^7$. There has also been a considerable increase in the quantity and quality of transition probabilities which can be measured with uncertainties smaller than 20% (<0.1 dex for $\log(gf)$). Elements such as Sc, V, Mn, Fe, Co or Ni have been carefully studied by groups at Imperial College London (UK), the National Institute of Standards and Technology (NIST) (US), the Universities of Lund and Malmö (Sweden) or the University of Wisconsin-Madison (US) (Pickering et al. (2019)). Table 3 includes examples of some of the work performed by these groups during the last 5 years (works done in collaboration between different groups

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

**Table 2.** Overview of some of the main Galactic Surveys.

| Galactic Survey | Telescope | Spectrograph | Location | Year |
|---|---|---|---|---|
| **APOGEE-1** (SDSS-III)[1] | Sloan Foundation Telescope (2.5 m) | APOGEE-N | Apache Point Observatory (USA) | 2008-2014 |
| **APOGEE-2** (SDSS-IV)[2] | Irénée du Pont Telescope (2.5 m) | APOGEE-S | Las Campanas Observatory (Chile) | 2014-2020 |
| **Gaia-ESO** | VLT (8.2 m) (Very Large Telescope) | FLAMES (UVES + GIRAFFEE) | Cerro Paranal (Chile) (European Southern Observatory) | 2014-2019 |
| **GALAH** | Anglo-australian telescope (3.9 m) | HERMES | Siding Spring Observatory (Australia) | 2014- |
| **WEAVE** | William Herschel Telescope (4.2 m) | WEAVE | Canary Islands (Spain) | 2022- |
| **4MOST** | VISTA telescope (4 m) | 4MOST | Cerro Paranal (Chile) (European Southern Observatory) | ∼2024 |

*Notes:*
[1]SDSS-III: Third Sloane Digital Sky Survey
[2]SDSS-III: Fourth Sloane Digital Sky Survey

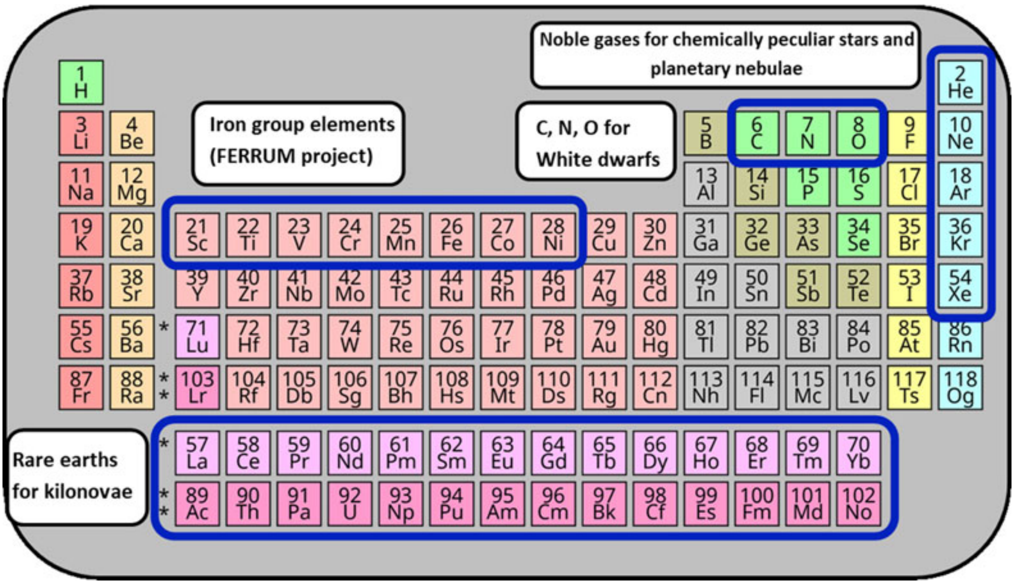


**Figure 1.** Examples of atomic data needs for different astronomical objects.

are included in the institution of the first author). Papers providing transition probabilities normally include these values as $\log(gf)$ too (where $f$ is the oscillator strength). Despite the improvements in atomic data shown in Table 3, there are still many spectral lines which continue to appear in the "wish lists" of astronomers, so experimental work on these elements should definitely be continued. We must not forget either that the launching of the *James Webb Space Telescope* (Gardner et al. (2006)) on December 2021 will no doubt increase the need for high-quality atomic data of these elements in the infrared region.

Since 2017, a renewed interest in the atomic data of the heavy elements has swept across the globe. The detection of the merging of two neutron stars for the very first time, both as a gravitational wave and as emission of radiation known as a kilonova

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

**Table 3.** Examples of experimental work on atomic data carried out during the last 5 years.

| Group | Element | Atomic Parameter provided[1] | Reference |
|---|---|---|---|
| Imperial College London (UK) | Ni II | Wavelengths, energy levels | Clear et al. (2022) |
| | Mn II (forbidden lines) | Wavelengths, transition probabilities | Liggins et al. (2021b) |
| | Mn II | Wavelengths, energy levels | Liggins et al. (2021a) |
| | Co II | Hyperfine structure constants | Ding & Pickering (2020) |
| | Fe I | Transition probabilities | Belmonte et al. (2017) |
| NIST (US) | Sc I and II | Hyperfine structure constants | Hala & Nave (2022) |
| | Si II, C II, Fe I, Ni II | Wavelengths | Nave & Clear (2021) |
| | Fe V, Ni V | Wavelengths and energy levels | Ward et al. (2019) |
| Universities of Lund and Malmö (Sweden) | Nb II | Transition probabilities | Nilsson et al. (2019b) |
| | V II | Transition probabilities | Nilsson et al. (2019a) |
| | Sc II | Transition probabilities | Pehlivan Rhodin et al. (2017) |
| | Mg I | Transition probabilities | Rhodin et al. (2017) |
| University of Wisconsin (US) | Hf II | Transition probabilities | Den Hartog et al. (2021) |
| | Lu II | Hyperfine structure constants | Den Hartog et al. (2020) |
| | Sc I and II | Transition probabilities | Lawler et al. (2019) |
| | V I | Transition probabilities | Wood et al. (2018) |
| | Co II | Transition probabilities | Lawler et al. (2018) |
| | Cr II | Transition probabilities | Lawler et al. (2018) |

*Notes:*
[1]Normally papers providing transition probabilities also include these values as $\log(gf)$ ($f$ is the oscillator strength)

(Kasen et al (2017)), has sparked the interest of the scientific community for the heavier elements of the periodic table. This can be seen in the increased number of talks about heavy elements during this IAUGA symposium. Astronomers are trying to answer questions such as where elements such as gold or the so-called rare earths were formed. The analysis and interpretation of the kilonovae spectra recorded during merger GW170817 could hold the key to answer some of these questions. Several groups are working very actively on the theoretical calculation of wavelengths, energy levels and transition probabilities for heavy elements: a group in Los Alamos (Fontes et al. (2020), Fontes et al. (2022)), a Lithuanian-Japanese collaboration (Tanaka et al. (2020)) and other collaborations such as Silva et al. (2022).

Not only the iron-group and the heavy elements populate the "wish lists" of astronomers. For example, astronomers working on the field of white dwarfs are still in need of atomic data for elements such as C, N and O (Hoskin et al. (2020)). Despite the available compilations for elements such as C (Haris & Kramida (2017), Kramida & Haris (2022)), there are still lines in the spectra of white dwarfs that cannot be identified or for which the transition probabilities are not available or have poor quality.

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

**Table 4.** Chemically peculiar stars of the upper main sequence.

| Name | CP group | Temperature (K) | Overabundance noble gases |
|---|---|---|---|
| Metallic-line (Am) | CP1 | 7 000-10 000 | |
| Magnetic (Bp-Ap) | CP2 | 7 000-16 000 | Xe |
| HgMn | CP3 | 10 500-16 000 | Xe |
| He-weak | CP4 | 14 000-20 000 | |

Traditionally, our laboratory (the Atomic Spectroscopy Laboratory at the University of Valladolid, Spain) has focused on the measurements of atomic parameters for the noble gases, also of great importance for astronomers. Despite their relevance in a wide range of fields, such as fusion, laser production or lightening industry, the quantity and quality of data such as transition probabilities for noble gases still lies very far for the users' needs. As an example, a search for transition probability data for Xe II on the ASD database (Kramida et al. (2022)) in the spectral range 300 - 800 nm returns values for only 23 out of the 718 lines available. Noble gases such as Ar have been observed in the Crab nebula as a molecular ion (Barlow et al. (2013)). In the field of planetary nebulae, analysis of near-infrared emission spectra revealed the presence of Kr and Xe (Sterling (2020), Sterling et al. (2017)).

One of the most interesting examples of the need of atomic data for noble gases in astronomy is that one of the study of chemically peculiar stars (Bidelman (1962)). There are four main groups of chemically peculiar stars, CP1 (chemically peculiar type 1) to CP4. The main characteristics of the different types are summarised in Table 4.

As shown in the third column of Table 4, Bp and HgMn stars (types CP2 and CP3, respectively) have the peculiarity of presenting relatively high temperatures, ranging between 6000 and 16 000 K. These high temperatures determine the elements and the degrees of ionisation observed in the atmospheres of these stars. Bidelman (1962) suggested the presence of Xe and Kr in their atmospheres for the first time. More recent studies such as those of Smith (1996), Dolk et al. (2002) and Castelli et al. (2017) have shown that there is a high overabundance of Xe in HgMn and Bp stars with respect to that one present in the sun (see Fig. 2 in Dolk et al. (2002)). This need of Xe II transition probabilities for the analysis of CP stars, combined with a lack of experimental data, has been the motivation for the theoretical work of Di Rocco et al. (2015). Astronomers have also obtained transition probability values ($\log(gf)$) for Xe II using the so called astrophysical method (Yüce et al. (2011)). We have measured experimental transition probabilities in the UV-visible region using the Boltzmann-Plot technique and compared them with the theoretical and astrophysical values available in the literature (manuscript in preparation).

## 4. The Atomic Spectroscopy Laboratory

During the last 45 years, the Atomic Spectroscopy Laboratory at the University of Valladolid (Spain) has focused on the development and characterisation of a pulsed-discharge lamp and its use for the measurement of atomic parameters of noble gases. We measure transition probabilities and Stark parameters (Stark shifts and widths). The capabilities of our experimental set-up are shown in Table 5. The measurement of high-accuracy parameters is possible thanks to the high stability and repeatability of our pulsed-discharge lamp (del Val et al. (1998)) and to the ability to measure the temporal evolution of the electron density inside the discharge lamp using a two-wave interferometric technique (de la Rosa et al. (1990)). Our experimental set-up is shown in Fig. 2. A detailed description can be found in Belmonte (2016).

https://doi.org/10.1017/S1743921323000273 Published online by Cambridge University Press

**Table 5.** Atomic Spectroscopy Laboratory capabilities.

| | |
|---|---|
| **Spectrograph** | 1.5 m Jobin-Yvon monochromator (diffraction grating 2400 lines/mm) |
| **Resolving power** | 125 000 (at 400 nm) |
| **Spectral range** | 190-800 nm (UV-visible) |
| **Lamps** | Pulsed-discharge lamp (for noble gases)<br>Hollow-cathode lamp (for metals and rare earths) |
| **Ionisation achievable** | neutral, singly and doubly ionised (I, II and III) |
| **Aditional instrument** | Fabry-Pérot interferometer (Burleigh RC-Series) |

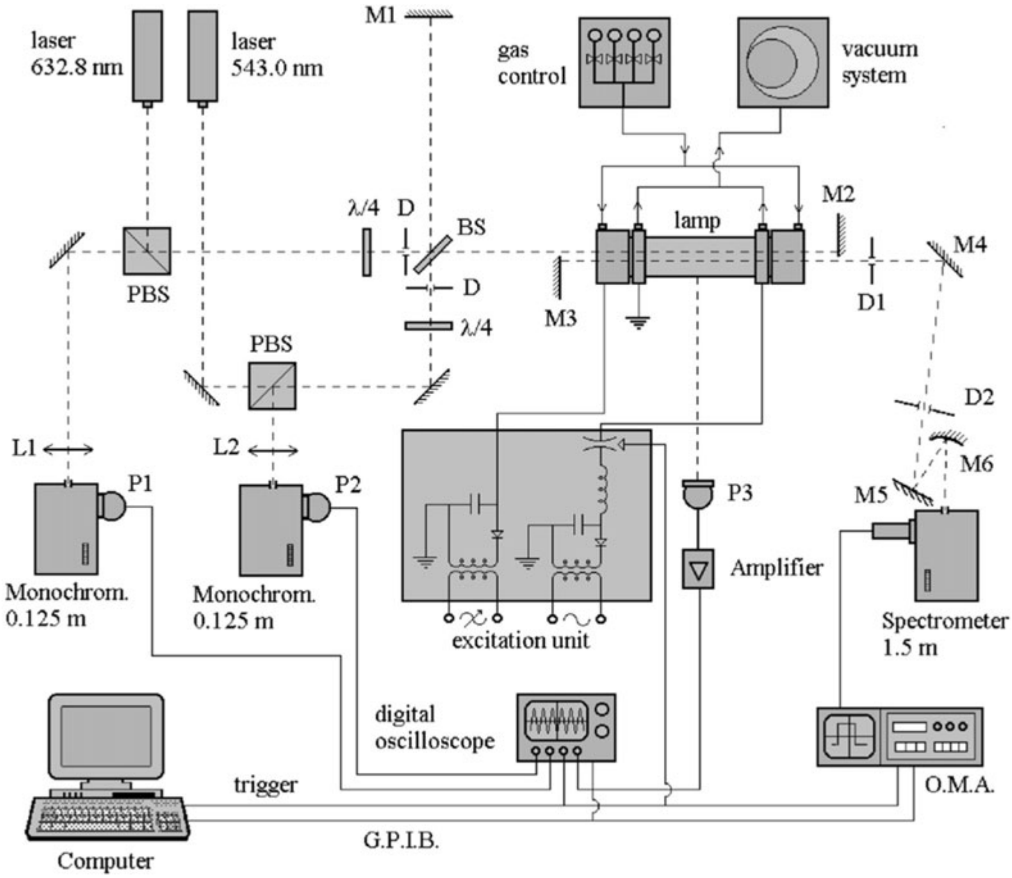


**Figure 2.** Experimental set-up with our pulsed-discharge lamp.

Our laboratory has measured transition probabilities and Stark parameters of neutral, singly and doubly ionised noble gases in a systematic way since 1991. By that stage, the laboratory had already been operative for 15 years working on the development of a stable pulsed-discharge lamp which fulfills the conditions of presenting a high symmetry, high repeatability and where the plasma created satisfies the conditions of pLTE (partial local thermodynamic equilibrium) at least within a given range of energy levels (Aparicio et al. (2012)). Examples of our latest work can be found in Belmonte et al. (2014), Belmonte et al. (2016) and Belmonte et al. (2021).

After closing 4 years ago due to the retirement of its PI, the Atomic Spectroscopy Laboratory at the University of Valladolid reopened in April 2021 thanks to funding provided by both the Spanish Government (with a “Beatriz Galindo” Fellowship granted to the first author) and by the University of Valladolid (through their Research Project grants for emerging groups). Building on the immeasurable quantity of work and money invested over the last 45 years, our aim is to adapt the laboratory to measure data for some of the most current pressing needs in astrophysics. In particular, we are going to focus on the heavy elements due to their relevance for the study of kilonovae spectra. To perform these measurements, we have equipped our laboratory with a hollow-cathode lamp built in our workshop following the design of the one used at Imperial College London (lamp plans and advice kindly provided by Prof J. Pickering and her group at Imperial College London). We have adapted this design to fit the specific needs of our laboratory.

There is a considerable difference between the spectra of noble gases and the very complex and dense spectra of heavy elements. To undertake this new project in our laboratory, we are working together with Prof Pickering's group at Imperial College London. We will carry out measurements using the Fourier Transform Spectrometer (FTS) at Imperial College (Belmonte et al. (2018)) and compare them with spectra obtained on our grating instrument. Grating spectroscopy has the advantage that weak spectral lines do not get lost in the noise, as it happens with fourier transform spectroscopy. Therefore, by combining instruments, we will enjoy the advantages of both techniques: the high resolving power of the FTS at Imperial College (2 000 000 at 200 nm) and the ability to see weak lines provided by our grating spectra. We are also setting-up a Burlington RC-Series Fabry-Pérot interferometer with which we will be able to measure at much higher resolving powers.

## Acknowledgements

M. T. Belmonte acknowledges the funding provided by the University of Valladolid under the grant "Research projects UVa 2021" and by the Spanish government through a Distinguished Researcher "Beatriz Galindo" Fellowship. P. R. Sen Sarma thanks the University of Valladolid for his PhD grant.

## References

Aparicio, J.A., Belmonte, M.T., Peláez, R.J., Djurović, S. & Mar, S. 2012, *J. Phys. Conf. Ser.*, 399, 012012

Araujo-Hauck, C., Pasquini, L., Manescau, A., Udem, T., Hänsch, T.W., Holzwarth, R., Sizmann, A., Dekker, H., D'Odorico, S. & Murphy, M.T. 2007, *The Messenger*, 129, 24-26

Barlow, M.J., Swinyard, B.M., Owen, P.J., Cernicharo, J., Gomez, H.L., Ivison, R.J., Krause, O., Lim, T.L., Matsuura, M., Miller, S. & Olofsson, G. 2013, *Science*, 342(6164), 1343-1345

Belmonte, M.T., Djurović, S., Peláez, R.J., Aparicio, J.A. & Mar, S. 2014, *MNRAS*, 445(4), 3345-3351

Belmonte, M. T. 2016, *PhD Thesis*, University of Valladolid

Belmonte, M.T., Gavanski, L., Peláez, R.J., Aparicio, J.A., Djurović, S. & Mar, S. 2016, *MNRAS*, 456(1), 518-524

Belmonte, M.T., Pickering, J.C., Ruffoni, M.P., Den Hartog, E.A., Lawler, J.E., Guzman, A. & Heiter, U. 2017, *ApJ*, 848(2), 125

Belmonte, M.T., Pickering, J.C., Clear, C.P., Concepción Mairey, F. & Liggins, F. 2018, *Galaxies*, 6(4), 109

Belmonte, M.T., Gavanski, L., Djurović, S., Mar, S. & Aparicio, J.A. 2021, *J Quant Spectrosc Radiat Transf*, 271, 107703.

Bidelman, W. P. 1962, *ApJ*, 67, 111

Castelli, F., Cowley, C.R., Ayres, T.R., Catanzaro, G. & Leone, F. 2017, *A&A*, 601, A119

Clear, C. P., Pickering, J. C., Nave, G., Uylings, P., & Raassen, T. 2022, *ApJS*, 261(2), 35

Dalton, G. 2016, *ASP-CS*, 507, 97

de Jong, R.S., Agertz, O., Berbel et al. 2019, *The Messenger*, 175

de la Rosa, M. I., Pérez, M. C., de Frutos, A. M & Mar, S. 1990, *Phys. Rev. A*,42, 7389-7394

del Val, J. A., Mar, S., Gigosos, M.A., de la Rosa, I., Pérez, C. & González, V. 1998, *JJAP*, 37(7), 4177-4181.
Den Hartog, E. A., Lawler, J. E., & Roederer, I. U. 2020, *ApJS*, 248(1), 10
Den Hartog, E. A., Lawler, J. E., & Roederer, I. U. 2021, *ApJS*, 254(1), 5
Di Rocco, H.O., Cruzado, A. & Marchiano, P.E. 2015, *A&A*, 581, A63
Ding, M. & Pickering, J. C. 2020, *ApJS*, 251(2), 24
Dolk, L., Wahlgren, G.M., Lundberg, H., Li, Z.S., Litzén, U., Ivarsson, S., Ilyin, I. & Hubrig, S. 2002, *A&A*, 385(1), 111-130
Fontes C. J., Fryer C. L., Hungerford A. L., Wollaeger R. T.& Korobkin O. 2020, *MNRAS*, 493, 4143
Fontes, C.J., Fryer, C.L., Wollaeger, R.T., Mumpower, M.R. & Sprouse, T.M. 2021, *MNRAS*, stac2792
Gardner, J.P., Mather, J.C., Clampin, M. et al. 2006, *Space Sci. Revs*, 123(4), 485-606
Gilmore, G., Randich, S., Asplund, M., Binney, J., Bonifacio, P., Drew, J., Feltzing, S., Ferguson, A., Jeffries, R., Micela, G. & Negueruela, I. 2012, *The Messenger*, 147
Gilmore, G., Randich, S., Worley, C.C. et al. 2022, *A&A* ,666, A120
Hala & Nave, G. 2022, *ApJS*, 259(1), 17
Haris, K. & Kramida, A. 2017, *ApJS*, 233(1), 16
Hatzes, A.P. 2016, *Springer, Cham*, In Methods of Detecting Exoplanets, pp. 3-86
Hoskin, M.J., Toloza, O., Gänsicke, B.T. et al. 2020, *MNRAS*, 499(1), 171-182
Johansson, S., Derkatch, A., Donnelly, M.P., Hartman, H., Hibbert, A., Karlsson, H., Kock, M., Li, Z.S., Leckrone, D.S., Litzén, U. & Lundberg, H. 2002, *Physica Scripta*, T100, 71
Kasen, D., Metzger, B., Barnes, J. et al. 2017, *Nature*, 551, 80–84
Kramida, A., & Haris, K. 2022, *ApJS*, 260(1), 11
Kramida, A., Ralchenko, Yu., Reader, J. & NIST ASD Team 2022, NIST Atomic Spectra Database (ver. 5.10), [Online] https://physics.nist.gov/asd, National Institute of Standards and Technology, Gaithersburg, MD.
Lawler, J. E., Sneden, C., Nave, G., Den Hartog, E. A., Emrahoglu, N., & Cowan, J. J. 2017, *ApJS*, 228(1), 10
Lawler, J. E., Feigenson, T., Sneden, C., Cowan, J. J., & Nave, G. 2018, *ApJS*, 238(1), 7
Lawler, J. E., Sneden, C., Nave, G., Wood, M. P., & Cowan, J. J. 2019, *ApJS*, 241(2), 21
Liggins, F. S., Pickering, J. C., Nave, G., Ward, J. W., & Tchang-Brillet, W. Ü. L. 2021, *ApJS*, 252(1), 10
Liggins, F. S., Pickering, J. C., Nave, G., Kramida, A., Gamrath, S., & Quinet, P. 2021, *ApJ*, 907(2), 69
Majewski, S.R., Schiavon, R.P., Frinchaboy, P.M. et al. 2017, *AJ*, 154(3), 94
Murphy, M.T., Molaro, P., Leite, A.C., Cupani, G., Cristiani, S., D'Odorico, V., Santos, R.G., Martins, C.J., Milaković, D., Nunes, N.J. & Schmidt, T.M. 2022, *A&A*, 658, A123
Nave, G., & Clear, C. 2021, *MNRAS*, 502(4), 5679-5685
Nilsson, H., Andersson, J., Engström, L., Lundberg, H., & Hartman, H. 2019, *A&A*, 622, A154
Nilsson, H., Engström, L., Lundberg, H., Hartman, H., Palmeri, P., & Quinet, P. 2019, *A&A*, 627, A102
Pasquini, L., Avila, G., Blecha, A. et al. 2002, *The Messenger*, 110, 1-9
Pehlivan Rhodin, A., Belmonte, M.T., Engström, L., Lundberg, H., Nilsson, H., Hartman, H., Pickering, J.C., Clear, C., Quinet, P., Fivet, V. & Palmeri, P 2017, *MNRAS*, 472(3), 3337-3353
Pepe, F., Cristiani, S., Rebolo, R. et al. 2021, *A&A*, 645, A96
Pickering, J.C., Belmonte, M.T., Clear, C.P., Liggins, F. & Concepcion-Mairey, F. 2019, in: F. Salama & H. Linnartz (eds.), *Laboratory Astrophysics: from Observations to Interpretation*, Proc. IAU Symposium No. 350, 15(S350), p220-228
Picqué, N. & Hänsch, T. W. 2019, *Nat. Photon*, 13(3), 146-157
Preston, G.W. 1974, *ARAA*, 12, 257-277
Rhodin, A. P., Hartman, H., Nilsson, H., & Jönsson, P. 2017, *A&A*, 598, A102
Schöller, M. 2007, *New Astron. Revs*, 51(8-9), 628-638

Silva, R.F., Sampaio, J.M., Amaro, P., Flörs, A., Martínez-Pinedo, G. & Marques, J.P. 2022, *Atoms*, 10(1), 18

Smith, K.C. 1996, *Ap&SS*, 237(1), 77-105

Sterling, N.C., Madonna, S., Butler, K., García-Rojas, J., Mashburn, A.L., Morisset, C., Luridiana, V. & Roederer, I.U. 2017, *ApJ*, 840(2), 80

Sterling, N.C. 2020, *Galaxies*, 8(2), 50

Tanaka M., Kato D., Gaigalas G. & Kawaguchi K. 2020, *MNRAS*, 496, 1369

Ward, J. W., Raassen, A. J. J., Kramida, A., & Nave, G. 2019, *ApJS*, 245(2), 22

Wood, M. P., Sneden, C., Lawler, J. E., Den Hartog, E. A., Cowan, J. J., & Nave, G. 2018, *ApJS*, 234(2), 25

Yüce, K., Castelli, F. & Hubrig, S. 2011, *A&A*, 528, A37