Applications of Helium-4 Doubly Forbidden Singlet-Triplet Transition Lines in Astronomical Spectroscopy

Christine Ye
Independent Researcher, Eastlake High School, Sammamish, WA

***Abstract*—Helium-4, the most common isotope of helium, is difficult to detect in the interstellar medium, as classical transitions are moderately rare; however, Helium-4 also can undergo forbidden transitions. One of these, between metastable states of Helium-4 in the 2s energy level, occurs experimentally at 1557nm in the near-infrared range; it is lower in energy and less subject to dust extinction, making it an excellent choice for the cold and warm neutral mediums. A sample of 50 nearby spiral galaxies were chosen for the study, a mostly homogeneous population. Near-infrared and radio spectra were processed, reduced, and analyzed through an independently developed procedure to correct errors, and to determine the spectral flux of the Doppler-broadened 1557nm line using a Gaussian line fit and a polynomial background approximation. Overall, in 31 of the 50 galaxies, the line was detected at a statistically significant level with high confidence, and in 6, it was detected with moderate confidence. In addition, in the sample galaxies, as expected, the spectral line flux correlated with overall H-band magnitude as defined by the astronomical magnitude system, confirming the accuracy and potential of this spectral line. Preliminary work has been undertaken for the study of the 1557nm spectral line in main sequence and post-MS stars, including the development of a procedure to adjust for errors and perform a Voigt approximation, as well as some spectral analysis. Forbidden transition spectroscopy in Helium-4, in the future, may serve as a useful tool for mapping and tracing states and masses of helium in the universe, leading to a variety of insights. As a proof of concept, a set of equations have been derived to calculate the mass of Helium-4 in the galaxy from spectral flux. The 1557nm spectral line has the potential to be a detectable and significant source of data for future study of low-energy Helium-4.**

I. Introduction and Rationale

Spectroscopy and spectral line mapping is a quickly growing field of observational and data-intensive astronomy, particularly in relation to the HI spin-flip line at 21cm, which has greatly improved our understanding of neutral hydrogen's distribution in the interstellar medium [2]. In particular, spectral line mapping is particularly useful for tracing clouds of low-energy, ground state hydrogen which are traditionally difficult to detect due to weak background radiation [6]. Presently, similarly to hydrogen, there are few reliable ways to detect the distribution of neutral stable and metastable Helium-4 in galaxies and gas clouds, especially for helium in the interstellar medium where classical and quantized excitation and deexcitation is relatively rare as a result of weak radiation fields in these areas [3]. Despite Helium-4's role as the second most common atom in the universe, including the interstellar medium, neutral helium's presence and mass generally must be inferred from other, often inconclusive or unreliable, methodologies; these are often subject to dust extinction and other uncertainties.

Research and investigation into the use of singlet-triplet transition lines would allow a better understanding of the presence and distribution of neutral helium in the universe, and an additional data source for understanding the composition of galaxies, thus helping to elucidate stellar and galactic evolution and structure, as well as the primordial helium mass fraction, among other applications.

II. Spectral Feature Characteristics

The Helium-4 forbidden transition line investigated here is the singlet-triplet feature on the metastable 2s energy level, prevalent in the interstellar medium with relatively high excitation times (approx. 8000s for the triplet state, $^3S_1$, and 20ms for the singlet state, $^1S_0$) [4]. These states differ in their magnetic dipole spins (spin-parallel and spin-antiparallel) and quantum degeneracy.
Triplet States:

$$|S=1, M_s=1\rangle = |\uparrow,\uparrow\rangle \tag{1}$$

$$|S=1, M_s=-1\rangle = |\downarrow,\downarrow\rangle \tag{2}$$

$$|S=1, M_s=0\rangle = \frac{1}{\sqrt{2}}\,|\uparrow,\downarrow\rangle + |\downarrow,\uparrow\rangle \tag{3}$$

Singlet State:

$$|S=1, M_s=0\rangle = \frac{1}{\sqrt{2}}\,|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle \tag{4}$$

Both states are possible in the 2s energy, even for the bosonic Helium-4 atom, by the Pauli Exclusion Principle. The energy difference has been experimentally confirmed to be 1557 nm (1.557 μm) [5]. In the interstellar medium, the line should appear with redshifting in the near-infrared as an absorption feature, due to the low temperature of the interstellar medium [6]. Given the variability of galaxies in the near-infrared and the emission-dominated stellar emission spectra that make up galaxy spectra, caution must be taken in spectral analysis. The singlet-triplet spin temperature is calculated to be 3.34 in the Warm Neutral Medium (WNM) and 1.06 in the Cold Neutral Medium (CNM).

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} e^{\frac{-hv_{10}}{kT_s}} \tag{5}$$

The Einstein A-Coefficient (spontaneous emission) is approximately $6.11 * 10^{-8}$/s [7]. It follows that the Einstein B-Coefficient for stimulated absorption in a radiation field is approximately 0.00463/s. This B_{12} value can be used to calculate the rate of change in state density based on radiation and the volume of matter, which is explored later in this paper.

III. Spectral Data

This research aims to provide an initial investigation into Helium-4 forbidden spectral features, and will involve processing spectral data from a roughly homogeneous (morphology, evolutionary history, inclination with respect to Earth, redshift, total spectral flux/brightness, thermal continuum shape) galaxy sample, with the end result being a uniform medium for comparison of spectral flux and overall H-band near-infrared magnitude. Spectra in the HI radio (21cm) and near-infrared (NIR) electromagnetic ranges were collected and processed from 50 low-redshift galaxies - 39 Seyfert/LINER AGN spiral galaxies, 5 Seyfert/LINER AGN elliptical galaxies, and 6 HII spiral galaxies. Elliptical and HII galaxies were studied as a preliminary expansion, to investigate the presence of the line in galaxies with variable composition, neutral gas content, and stellar velocity dispersions [8]. Necessary adjustments were made to the reduction and processing procedure for these specimens.

Radio spectra were accessed through the NASA/IPAC extragalactic database [9]. Spectra were taken using various radio telescopes by several parties, including the Arecibo 305m, the Green Bank 91m, and others. In general, the radio spectra are characterized by medium resolution and high signal to noise (SNR) with distinct dual horned structure. Radio spectra were pre-processed via pipeline for Hanning smoothing, averaging, baseline subtraction, etc. Near-infrared spectra were taken between 8000A and 25000A, with a resolution of 16A and a step of 2.4A, using XD on the Gemini North telescope's infrared spectrograph (XDGNIRS) by Mason et al. [10]. Spectra were taken between 2011 and 2013 with variations in observing conditions and time, and a chopping/nodding pattern applied to XDGNIRS. The data is characterized by high SNR (>20) with poor spectra omitted from the sample, and was pipeline processed for striping, cosmic rays, spectrograph irregularities and configuration, atmospheric/telluric absorption, and other noise. Spectra for HII galaxies were taken at the NASA 3m Infrared Telescope Facility with similar conditions and processing by Martins et al. [11].

IV. Data Reduction and Processing

After pre-project pipeline processing, calculations and adjustments were performed to adjust for redshift, broadening, display, and galactic thermal continua. Spectral lines were approximated using Gaussian fits for Doppler-broadened spectral lines and integrated for total flux [12]. Galactic spectral redshift is due to Hubble expansion of the universe, outside gravitational influence, and spiral galaxies' rotation. The quantity (z-parameter) of redshift was determined by measuring neutral hydrogen in a 21cm/HI spectrum. The dual peaks/horns in HI spectra for spiral galaxies were recorded and analyzed to determine the recessional velocity of the galaxy's receding and approaching sides, which yielded both total average redshift and rotation rate.

$$z = \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} - 1 \tag{6}$$

The calculated z-parameter was then used to determine the expected wavelength and full width at half maximum (FWHM) of the redshift-broadened Gaussian spectral feature, usually approx. 20A. Inclination was accounted for in considering the full dataset; face-on galaxies of course have much lower radial rotational velocities than edge-on galaxies.

Other broadening sources included Heisenberg effect energy uncertainty, the Zeeman and Stark effects (splitting and shifting), and collisional/thermal broadening. Due to the metastable lifetime of the singlet and triplet states, expected energy uncertainty is extremely low (compared to rotational Doppler broadening) and thus negligible. The Zeeman and Stark effects, likewise, are negligble due to the weakness of the interstellar magnetic and electric fields. Thermal Doppler broadening (due to random kinetic motion of atoms) is also insignificant compared to rotational broadening and low temperatures in the WNM and CNM, and collisional broadening is mostly negligible due to the low density and velocity dispersions in the ISM. The linewidth and shape should roughly follow the predicted Doppler rotation-broadened Gaussian fit.

Data was calibrated, adjusted for units, displayed, and fit in SPLAT software [13]. In SPLAT, errors and outstanding features from telluric absorption and emission and other residual spectral sources, including the H-band bump, high blue-end dust absorption, and strong stellar features, were masked. In NGC 3031, for example, regions of poor atmospheric tranmission and several broad and narrow lines characteristic of Seyfert 1 galaxy spectra, were removed [9, 10].

Galaxy thermal continua, consisting of overlapping Planck blackbody functions at various temperatures and redshifts, are approximately smooth. In small to medium wavelength ranges, the galaxy spectra were smooth enough to be represented by a medium to high-degree polynomial fit. Supervised polynomial regressions were performed on the masked data; continuum spectra were subtracted as ceilings to reveal absorption features, which exist outside of the thermal continuum [16].

Based on high redshift and rotation, as well as other broadening sources, the galactic spectral features in question (Helium-4 singlet-triplet absorption lines) were approximately represented as Gaussians, a close fit with Poisson curves. A local low-degree baseline was estimated to confirm the accuracy of the high-degree polynomial within a much smaller wavelength range. The Gaussian fit was performed using supervised regression at the calculated wavelength and redshift FWHM. Supervised multiple Gaussian regressions were performed for areas with overlapping spectral features, common in the noisy near-infrared, improving accuracy.

$$\frac{1}{2\pi\sigma} e^{\frac{-x^2}{2\sigma^2}} \tag{7}$$

Flux was determined by integrating between the thermal continuum background and the spectral Gaussian, and calculated in both energy density and total photonic spectral irradiance.

V. Preliminary Study of Stellar Spectra

Preliminary work on procedures for processing forbidden spectral lines in the spectra of stars, especially cool main-sequence (KM) stars, has been developed and tested with a small sample, although the need for forbidden line spectroscopy is not as great as with galaxies due to the stronger radiation fields. However, these lines may still be used to study the interior of the star's atmospheric gases. The primary sources of spectral broadening are rotational Doppler broadening, thermal Doppler broadening (due to the high temperatures of stellar atmospheres), and collisional uncertainty broadening (due to high density and kinetic energy). Rotation rates and decay of stellar rotation have been calculated in the past [14]. Zeeman and Stark splitting and shifting are significant in stars due to the high field strengths. Well-known spectral emission features, i.e. the Balmer series, the Pickering series for Helium-4, and individual metal lines were used to determine redshift; specific lines were chosen based on stellar temperature and spectral clarity on a star-to-star basis. Using a Voigt fit, ideal for lines with diverse broadening (both Doppler and collisional), recessional and rotational velocities were determined to extrapolate the 1557nm line's expected position and width. Background continua were fit using supervised regressions with error/outstanding feature masking. Peak wavelength was determined from fit and used to calculate temperature, which informed other parts of the procedure (i.e. spectral line subtraction). Spectral lines were fitted at calculated FWHM and wavelength with a Voigt fit. The stellar final procedure was tested with flux-normalized data by Ivanov et al., using 10 stars of various luminosity classes and spectral types with data taken from the Steward Observatory Bok telescope [15].

VI. Results and Analysis

50 galaxies were processed in this study to determine the presence of the singlet-triplet line in the 2s level in Helium-4 atoms at 1557nm. Statistical analysis of spectral flux was performed by calculating signal to noise (SNR) of the spectral lines using various approximations for source Poisson/shot noise, readnoise, skynoise, background noise, darknoise, sharpness, and instrument noise, based on information regarding observation (i.e., time, cloud cover, etc.) and instrumentation. Overall, 31 galaxies had $\frac{S}{N}$ values > 3, indicating a significance level of 3σ, statistically significant findings, and high confidence in the detection of the spectral line. 6 galaxies had $\frac{S}{N}$ in the range of $1.5 < x < 3$, indicating moderate confidence in detection. Other galaxies, due to low flux, high error rates, poor observation

conditions, and other characteristics, had $\frac{S}{N}$ values < 1.5, indicating low confidence and significance.

$$S = Flux \tag{8}$$

$$N = \sqrt{Flux + (readnoise^2 + P_{dark}(t * 46) + P_{sky}t + Pbackground * t)/sharpness} \tag{9}$$

In the future, with greater exposure times and higher-quality, more frequent observing runs, these statistics are likely to improve. Possible variations in photon flux over the time interval were determined using the noise values and treated as errors; sources include data approximations in reduction, errors or variability in regression fitting, source noise, dust absorption, and background/sky noise. An expected outcome was that flux should roughly correlate with astronomical magnitude specifically within the NIR H-band. Galaxies with poor SNRs were eliminated; the galaxies with statistically significant findings were plotted against H-band magnitudes with errors accounted for; as predicted by the astronomical magnitude system, lower magnitude/higher brightness strongly correlated with higher photon flux of the absorption line. The 31 statistically significant detections, and the strong correlation, together suggest that this spectral line is detectable and significant as a future data source.

VII. Mass Calculations

Analogous to the HI 21-cm line, the photonic spectral irradiance of the 1557nm is directly related to the column density and thus mass of metastable Helium-4 in source galaxies [17]. Specifically, assuming low H band opacity (i.e., nearly all absorption signal transmitted) and utilizing other relationships (see section 1), the number of atoms of Helium-4 in the 2s triplet metastable state is equal to the transition energy density over the transition rate.

$$M_{He_{3S1}} \propto \frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{12} \int_{v_0}^{v} \rho(v)\, dv} \tag{10}$$

Spin temperature can be utilized to determine the total mass of Helium-4 in the 2s level.

$$M_{He_{2s}} \propto \frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{21} \int_{v_0}^{v} \rho(v)\, dv} + \frac{g_2}{g_1} e^{\frac{-hv_{10}}{kT_s}} \frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{12} \int_{v_0}^{v} \rho(v)\, dv} \tag{11}$$

Using the Boltzmann equation for excitation equilibrium and assuming Local Thermal Equilibrium (LTE) in the ISM, total neutral Helium-4 can be determined when evaluated assuming Maxwellian electron distributions.

$$M_{HeI} \propto \int_0^{\infty} [\frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{12} \int_{v_0}^{v} \rho(v)\, dv} + \frac{g_{N+1}}{g_N} e^{\frac{-hv_{10}}{kT_s}} \frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{12} \int_{v_0}^{v} \rho(v)\, dv}] \frac{g_{N+1}}{g_N} e^{\frac{E_N - E_{N+1}}{kT}} dN \tag{12}$$

Finally, assuming LTE again and using the Saha equation for ionization equilibrium, total Helium-4 can be extrapolated when evaluated with both Maxwellian ion and electron distributions.

$$M_{He} \propto \int_0^{\infty} 2 \frac{\int_0^{\infty} [\frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{12} \int_{v_0}^{v} \rho(v)\, dv} + \frac{g_{N+1}}{g_N} e^{\frac{-hv_{10}}{kT_s}} \frac{4\pi d^2 \int_{v_0}^{v} F(v)\, dv}{hvB_{12} \int_{v_0}^{v} \rho(v)\, dv}] \frac{g_{N+1}}{g_N} e^{\frac{E_N - E_{N+1}}{kT}} dN}{N_e} \frac{2m_e kT\pi}{h^2}^{\frac{3}{2}} \frac{g_{N+1}}{g_N} e^{\frac{-\chi}{kT}} dN \tag{13}$$

These equations have been derived and may one day serve as useful tools for the approximation of the mass of specific groups of Helium-4 (i.e., by energy level or ionization state). Evaluation should take into account dust extinction, ISM opacity, and galaxy inclination.

VIII. Summary

The primary applications of this spectral feature are tracing Helium-4 states and understanding the distribution and quantity of helium in galaxies and stars. Similar to HI, this line will serve as a source of novel data for the analysis of astronomical phenomena. Spectral line analysis and mass extrapolation may be used with the 1557nm line to determine Helium-4 distribution and mass in nuclei, arms, and disks of galaxies; the atmospheres of stars; globular and galactic clusters; the cosmic microwave background; post-Big Bang recombination; and others. Velocity-based wavelength measurements for galaxy and cluster rotation could be used to directly map the presence of Helium-4, similar to current HI efforts such as CHIME [2]. In addition, the mass determination equations previously derived could be useful in cosmology, by providing estimates for the mass of Helium-4 in galaxies and thus helping to provide evidence for or against the primordial helium mass fraction (currently approx. 25% by weight). Overall, this spectral line can provide information on gas clouds and helium areas that are not currently well understood across astronomy. Limitations include uncertainties in the data due to quantum mechanical effects, and some lacking analysis and modeling precision, especially for background and spectral feature fitting in galaxies due to their high variability. The data itself is also subject to precision-limiting factors, including calculation uncertainties (i.e. redshift), broad features, Poisson noise, and general observation and instrumentation limitations.

In the future, analysis of other forbidden, fine and hyperfine transitions should be analyzed in the Helium-4 atom, as well as other common atoms if possible (i.e., exploring other hydrogen lines). This would increase the data resources available for forbidden line spectroscopy applications. In addition, data collection and reduction methodology can be improved through further development in instrumentation and mathematical analysis/approximation, reducing error and uncertainty. Orbiting NIR observatories such as Spitzer, improved CCDs, refined calibration and observing patterns, increased exposure time and observing runs for higher SNRs, improved models (i.e. spectral libraries) for continua and spectral features, improved mathematical models for spin state, excitation, and ionization equilibriums, and new corrections (i.e., k-corrections for energy based on redshift), and many other improvements, would all be incredibly useful endeavors both for the 1557nm line and for astronomical spectroscopy as a whole. Wider studies with increased and more diverse samples should be undertaken; mapping investigations should be worked on as well, in order to maximize the potential of the spectral line. Despite its limitations, further study may potentially provide a wealth of new spectroscopic data and findings.

IX. References

[2] Bandura, Kevin, et al. "Canadian Hydrogen Intensity Maping Experiment (CHIME) Pathfinder." arXiv, 9 Jun. 2014. arxiv.org/abs/1406.2288

[3] Klessen, Ralf S., and Glover, Simon C. O. "Physical Processes in the Interstellar Medium." arXiv, 16 Dec. 2014. arxiv.org/pdf/1412.5182.pdf

[4] Van Leeuwen, K. A. H., and W. Vassen. "Helium 2 3S - 2 1S metrology at 1.557 m." arXiv, 11 Sept. 2006, arxiv.org/pdf/physics/0609087.pdf.

[5] Rubensson, Jan-Erik, et al. "Experimental Confirmation of Photon-Induced Spin-Flip Transitions in Helium via Triplet Metastable Yield Spectra." Physical Review A, 25 June 2010, journals.aps.org/pra/abstract/10.1103/ PhysRevA.81.062510.

[6] Hagen, J.P., et al. "Absorption of 21-cm Radiation by Interstellar Hydrogen." The Astrophysical Journal, Nov. 1995. adsbit.harvard.edu//full/1955ApJ...122..361H/0000365.000.html

[7] Baklanov, E. V., and Desinov, A. V. "The forbidden transition probability of 2 1S0 - 2 3S1 in helium atoms." Quantum Electronics, 1997. www.mathnet.ru/php/archive.phtml?wshow=paperjrnid=qepaperid=963

[8] Mogotsi, Keoikantse Moses, and Romeo, Alessandro B. "The stellar velocity dispersion in nearby spirals: radial profiles and correlations." arXiv, 26 Apr. 2018. arxiv.org/pdf/1804.10119.pdf

[9] "Object Spectra." NASA/IPAC Extragalactic Database, California Institute of Technology, ned.ipac.caltech.edu/. [10] Mason, R. E., et al. "The Nuclear Near-Infrared Spectral Properties of Nearby Galaxies." The Astrophysical Journal Supplement Series, 24 Mar. 2015. arXiv, arxiv.org/abs/1503.01836. Accessed 9 Mar. 2019.

[11] Martins, Lucimara P. et al. "A spectral atlas of HII galaxies in the near-infrared." Monthly Notices of the Royal Astronomical Society, 11 May 2013. academic.oup.com/mnras/article/431/2/1823/1466197

[12] North, Simon W. et al. "Line shape analysis of Doppler broadened frequency-modulated line spectra." The Journal of Chemical Physics, Oct. 1995. aip.scitation.org/doi/abs/10.1063/1.470969

[13] Draper, Peter W. "SPLAT: Spectral Analysis Tool." Astrophysics Source Code Library, Feb. 2014. adsabs.harvard.edu/abs/2014ascl.soft02007D.

[14] McNally, D. "Stellar rotation." Science Progress, October 1965. www.jstor.org/stable/43419440?seq=1page$_s can_t ab_c$ontents.

[15] Ivanov, Valentin D., et al. "A Medium-Resolution Near-Infrared Spectral Library of Late Type Stars." arXiv, arxiv.org/pdf/astro-ph/0311596.pdf

[16] Hammer, Francois, and Hector Flores. "Studying Distant Galaxies: A Handbook of Methods and Analyses." arXiv, arxiv.org/pdf/1701.03794.pdf.

[17] "Measuring the Neutral Hydrogen Mass of Galaxy Cluster A262." Monthly Notices of the Royal Astronomical Society, aip.scitation.org/doi/pdf/10.1063/ 1.4803561?class=pdf.