Echelle Grating Spectroscopic Technology Application

Subjects: Instruments & Instrumentation

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Echelle grating provides high spectral resolving power and diffraction efficiency in a broadband wavelength range by the Littrow mode. The spectrometer with the cross-dispersed echelle scheme has seen remarkable growth in recent decades. Rather than the conventional approach with common blazed grating, the cross-dispersed echelle scheme achieves the two-dimensional spatial distribution of the spectrum by one exposure without scanning in the broadband spectral range. It is the fastest and most sensitive spectroscopic technology as of now, and it has been extensively applied in commercial and astronomical spectrometers.

echelle grating spectrometer high-resolution

1. Commercial Instruments

The echelle system has been extensively used in commercial instruments because of its parallel measurement in a broadband spectral range with a high resolution and its compact size. The mainstream instruments include the inductively coupled plasma optical emission spectrometer (ICP-OES), atomic absorption spectrometry (AAS), and laser-induced breakdown spectroscopy (LIBS).

The combination of the echelle and cross-dispersion is the optimum optical scheme for ICP-OES that measures a large number of spectral lines simultaneously [1][2][3][4][5]. The spectral resolution is normally a few picometers. An echelle polychromator for ICP-OES designed by Thomas W in 1993 had a spectral range of 167–782 nm and a resolution of 0.006 nm (full width at half-maximum, FWHM) at 220 nm [2]. Shen Luan designed one that measured wavelengths from 130 nm to 800 nm, with a spectral bandwidth of 0.006 nm at 134.724 nm [1]. The near-infrared Echelle microwave-induced plasma atomic emission spectrometry (NIR-Echelle-MIP-OES) studied by J. Koch can be used for high-repetitive, high-resolved, and simultaneous spectra acquisition between 640 nm and 990 nm [3]. Chen proposed a wide spectral coverage approach with a rotating prism. The spectral range can reach 180–900 nm. Combined with ICP-OES, the wavelength precision is better than 0.01 nm [6]. Rolland-Thompson developed an approach in 2019 that can be applied to ICP-OES, and its imaging system includes primary, secondary, and tertiary tilted mirrors. The spectral resolution is up to 2.3 picometers/pixel [7].

The early AAS used hollow cathode lamps as the light source [8] and replaced the lamps to measure different chemical elements. Using continuous light as the light source directly is a challenge because it needs an optical scheme with a higher efficiency and a detector with more sensitivity [9]. The echelle cross-dispersed system provides a good solution [10]. For example, the electrothermal atomic absorption spectrometry (ETAAS) system developed by Bernard Radziuk determined simultaneous multi-elements and increased the radiation throughput [11]. Becker-Ross developed an echelle spectrometer as the research tool for the structured background in flame atomic absorption spectrometry (flame-AAS) with a spectral range of 200–465 nm [12].

LIBS requires broadband and high-resolution performance. In 1998, H.E. Bauer first proposed an approach using an echelle and an intensified charge coupled device (ICCD) in LIBS, which can simultaneously measure spectral lines in a wide wavelength range and improve the performance of analyzing samples [13]. Since then, the echelle scheme has been widely used in LIBS [14][15]. Chen Shao-jie [16] and C. Fabre [17] applied the echelle dispersion technique to LIBS successfully. A setup for LIBS and Raman spectroscopy measurements in a single unit using an echelle spectrograph system has been reported in recent years to measure minerals, archaeological artifacts, and other complex samples with minimum sample damage or consumption [18].

2. Astronomical Instruments

In the field of astronomy, spectral analysis is an extremely important way to observe celestial bodies. The spectral analysis determines the density, mass, movement, chemical composition, and distance from earth [19]. A high spectral resolution and broadband spectral range are the basic requirements for astronomical spectrometers. The light from deep space through a telescope is so weak that it usually takes more than one hour for an image. Spectrometers with common blazed gratings need multiple exposures for a broadband spectral range. During the longtime exposures, the state of celestial bodies may have changed. So, the capability of capturing the whole spectrum at one shot is another requisite for astronomical spectrometers. The echelle and the cross-dispersion are exactly applicable in astronomy.

Early astronomical applications of the echelle spectrometer include the middle ultraviolet solar spectrometer from rockets [20] and the echelle spectrometer-spectrograph for the 91 cm telescope at Pine Bluff [21]. However, due to the limitation of the grating fabrication, the resolution is not high. With the improvement of the ruling technique, echelle spectrometers have been more widely used [22]. The high-resolution echelle spectrometer (HIRES) [23][24] is the most representative one, which was constructed for the Keck telescope. It uses an echelle as the dispersive element, and the focal length of the collimator is much larger than that of the spectroscopic imaging mirror to reduce the image. It is difficult for the optical design to image the information from a large aperture telescope to the detector of a limited area. Therefore, the spectrometers for astronomical observation have much more complicated optics than commercial instruments. To meet the extremely high-resolution requirements, they typically have a front optical path, a collimated optical path, a cross-dispersion optical path, an imaging optical path, and an additional correction optical path.

In recent years, more and more observatories have begun to use echelle spectrometers for astronomical observations, as shown in **Table 1**. It can be seen that the spectral range of most spectrographs covers all of the visible spectrum and some of the near-infrared spectrum, such as EXPERT-III [25], CAFE [26], MIKE [27], and NRES [28][29][30]. There are also a few spectrometers whose spectral range only covers the near-infrared band, such as SPIRou [31][32][33]. Some spectrographs cover part of the mid-infrared spectrum, such as CRIRES+ [34][35][36][37].

Many of these spectrographs follow a concept called “white-pupil”, which was proposed by Baranne in 1972 [38]. In the white-pupil concept, the system pupil at the dispersive element is re-imaged on the entrance aperture of the camera. This pupil image is fixed at a specific position, independent of the wavelength. For example, the optical design of NEID is based on a classic white pupil layout [39]. Generally speaking, the white-pupil design offers a higher overall throughput and better image quality than conventional designs for the same resolution. For higher performance, some spectrometers use a beam splitter to split the beam into two sections so as to optimize the image quality and optical efficiency of each section individually. Some spectrometers split the beam into red and blue arms, such as G-CLEF [40][41][42], ESPRESSO [43][44][45][46], PEPSI [47][48][49][50], and SALT-HRS [51], while the light in CARMENES is separated into the visible and near-IR channels by a dichroic beam splitter centered at 0.96 µm [52][53][54]. In order to get a wider range of full spectrum coverage, some spectrographs employ several echelles with different incidence angles, such as CRIRES+.

Table 1. Echelle spectrometers at observatories.

Observatory	Spectrometer Model	Spectral Range (nm)	Resolution
Cala Alto Observatory	CAFE	365–980	70,000
	CARMENES	520–1710	93,400, 82,000
Cerro Tololo Inter-American Observatory	CHIRON [55]	410–880	80,000
European Southern Observatory	CRIRES+	950–5300	50,000, 100,000
	ESPRESSO	380–780	59,000, 134,000, ≈200,000
Kitt Peak National Observatory	EXPERT-III	380–900	56,000, 110,000
	NEID	380–930	100,000
Las Campanas Observatory	G-CLEF	350–950	19,000, 108,000
	MIKE	320–1000	19,000, 25,000
	NRES	390–860	53,000
	PFS [56]	388–668	38,000
Mauna Kea Observatory	IRD	970–1750	70,000
	SPIRou	980–2440	70,000
Mt. Graham International Observatory	PEPSI	384–913	50,000, 130,000, 250,000

Observatory	Spectrometer Model	Spectral Range (nm)	Resolution
South African Astronomical Observatory	SALT-HRS	370–890	15,000, 40,000, 65,000
Lijiang Observatory in China	CES [57]	570–1030	37,000

1. Luan, S.; Schleicher, R.G.; Pilon, M.J.; Bulman, F.D.; Coleman, G.N. An echelle polychromator for inductively coupled plasma optical emission spectroscopy with vacuum ultraviolet wavelength coverage and charge injection device detection. Spectrochim. Acta Part B At. Spectrosc. 2001, 56, 1143–1157.
2. Barnard, T.W.; Crockett, M.I.; Ivaldi, J.C.; Lundberg, P.L. Design and evaluation of an echelle grating optical system for ICP-OES. Anal. Chem. 1993, 65, 1225–1230.
3. Koch, J.; Okruss, M.; Franzke, J.; Florek, S.V.; Niemax, K.; Becker-Ross, H. Element-selective detection of gas chromatographic eluates by near infrared Échelle optical emission spectrometry on microwave-induced plasmas. Spectrochim. Acta Part B At. Spectrosc. 2004, 59, 199–207.
4. Zander, A.T.; Chien, R.L.; Cooper, C.B.; Wilson, P.V. An image-mapped detector for simultaneous ICP-AES. Anal. Chem. 1999, 71, 3332–3340.
5. Pilon, M.J.; Denton, M.B.; Schleicher, R.G.; Moran, P.M.; Smith, S.B. Evaluation of a New Array Detector Atomic Emission Spectrometer for Inductively Coupled Plasma Atomic Emission Spectroscopy. Appl. Spectrosc. 1990, 44, 1613–1620.
6. Chen, S.; Tang, Y.; Bayanheshig, X.; Qi, X.; Zhu, W. A new type of wide spectral coverage echelle spectrometer design for ICP-AES. In Optical Design and Testing V; SPIE: Bellingham, DC, USA, 2012; Volume 8557.
7. Rolland-Thompson, J.; Bauer, A.; Yates, D.; Farsad, M. Echelle Spectrometer for Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), Has Imaging System Comprises Primary, Secondary, and Tertiary Tilted Mirrors. U.S. Patent US546397P, 16 August 2019.
8. Salin, E.D.; Ingle, J.D. Performance of a time multiplex multiple slit multielement flame atomic absorption spectrometer. Anal. Chem. 1978, 50, 1745–1752.
9. Sneddon, J.; Farah, B.D.; Farah, K.S. Multielement Atomic Absorption Spectrometry: A Historical Perspective. Microchem. J. 1993, 48, 318–325.
10. Hamly, J.M. Multielement Atomic Absorption with a Continuum Source. Anal. Chem. 1986, 58, 933A–943A.
11. Radziuk, B.; Rdel, G.; Stenz, H.; Becker-Ross, H.; Florek, S. Spectrometer system for simultaneous multi-element electrothermal atomic absorption spectrometry using line sources and Zeeman-effect background correction. J. Anal. Atom. Spectrom. 1995, 10, 127–136.

12. Becker-Ross, H.; Okruss, M.; Florek, S.; Heitmann, U.; Huang, M.D. Echelle-spectrograph as a tool for studies of structured background in flame atomic absorption spectrometry. Spectrochim. Acta. Part B At. Spectrosc. 2002, 57, 1493–1504.
13. Bauer, H.E.; Leis, F.; Niemax, K. Laser induced breakdown spectrometry with an echelle spectrometer and intensified charge coupled device detection. Spectrochim. Acta. Part B At. Spectrosc. 1998, 53, 1815–1825.
14. Fichet, P.; Menut, D.; Brennetot, R.; Vors, E.; Rivoallan, A. Analysis by laser-induced breakdown spectroscopy of complex solids, liquids, and powders with an echelle spectrometer. Appl. Opt. 2003, 42, 6029–6035.
15. Hoehse, M.; Mory, D.; Florek, S.; Weritz, F.; Gornushkin, I.; Panne, U. A combined laser-induced breakdown and Raman spectroscopy Echelle system for elemental and molecular microanalysis. Spectrochim. Acta Part B At. Spectrosc. 2009, 64, 1219–1227.
16. Chen, S.; Qi, X.; Guo, T.Y.; Xia, Ù.C.H. A Portable Echelle Spectrograph Design for Laser-induced Breakdown Spectrometry. Chin. J. Lumin. 2013; 34, 672–677.
17. Fabre, C.; Dubessy, J.; Boiron, M.; Brennetot, R.; Fichet, P.; Vors, E.; Lacour, J.; Rivoallan, A. A LIBS spectral database obtained in Martian conditions with an echelle spectrometer for in situ analysis of Mars soils and rocks. In Laser Induced Plasma Spectroscopy and Applications; Optical Society of America: Washington, DC, USA, 2002; p. E3.
18. Shameem, K.M.; Dhanada, V.S.; Harikrishnan, S.; George, S.D.; Kartha, V.B.; Santhosh, C.; Unnikrishnan, V.K. Echelle LIBS-Raman system: A versatile tool for mineralogical and archaeological applications. Talanta 2020, 208, 120482.
19. Massey, P.; Hanson, M.M. Astronomical Spectroscopy. In Planets, Stars and Stellar Systems: Volume 2: Astronomical Techniques, Software, and Data; Oswalt, T.D., Bond, H.E., Eds.; Springer: Dordrecht, The Netherlands, 2013; pp. 35–98.
20. Tousey, R.; Purcell, J.D.; Garrett, D.L. An echelle spectrograph for middle ultraviolet solar spectroscopy from rockets. Appl. Opt. 1967, 6, 365–372.
21. Schroeder, D.J. An Echelle Spectrometer-Spectrograph for Astronomical Use. Appl. Opt. 1967, 6, 1976–1980.
22. Tousey, R. Highlights of twenty years of optical space research. Appl. Opt. 1967, 6, 2044–2069.
23. Epps, H.W.; Vogt, S.S. Extremely achromatic f/1.0 all-spherical camera constructed for the high-resolution echelle spectrometer of the Keck telescope. Appl. Opt. 1993, 32, 6270–6279.
24. Vogt, S.S.; Allen, S.L.; Bigelow, B.C.; Bresee, L.; Brown, W.E.; Cantrall, T.; Conrad, A.; Couture, M.; Delaney, C.; Epps, H.W.; et al. HIRES: The high-resolution echelle spectrometer on the Keck 10-m Telescope. In Instrumentation in Astronomy VIII; SPIE: Bellingham, DC, USA, 1994.

25. Ge, J.; Zhao, B.; Powell, S.; Wang, J.; Fletcher, A.; Chang, L.; Groot, J.; Wan, X.; Jakeman, H.; Myers, D.; et al. Design and Performance of a New Generation, Compact, Low Cost, Very High Doppler Precision and Resolution Optical Spectrograph. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy IV, Edinburgh, UK, 26–30 June 2016; Volume 8446.
26. Aceituno, J.; Sánchez, S.F.; Grupp, F.; Lillo, J.; Hernán-Obispo, M.; Benitez, D.; Montoya, L.M.; Thiele, U.; Pedraz, S.; Barrado, D.; et al. CAFE: Calar Alto Fiber-fed Echelle spectrograph. Astron. Astrophys. 2013, 552, A31.
27. Bernstein, R.A.; Shectman, S.A.; Gunnels, S.; Mochnacki, S.; Athey, A. MIKE: A double echelle spectrograph for the Magellan Telescopes at Las Campanas Observatory. In Instrument Design & Performance for Optical/Infrared Ground-Based Telescopes, PTS 1-3; SPIE: Bellingham, DC, USA, 2003; Volume 4841, pp. 1694–1704.
28. Eastman, J.D.; Brown, T.M.; Hygelund, J.; van Eyken, J.; Tufts, J.R.; Barnes, S. NRES: The Network of Robotic Echelle Spectrographs. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy V, Montréal, QC, Canada, 22–26 June 2014; Volume 9147.
29. Siverd, R.J.; Brown, T.M.; Hygelund, J.; Henderson, T.; Tufts, J.R.; Eastman, J.D.; van Eyken, J.; Barnes, S. NRES: The Network of Robotic Echelle Spectrographs. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy IV, Edinburgh, UK, 26–30 June 2016; Volume 9908.
30. Siverd, R.J.; Brown, T.M.; Barnes, S.; Bowman, M.K.; De Vera, J.; Foale, S.; Harbeck, D.R.; Henderson, T.; Hygelund, J.; Kirby, A.; et al. NRES: The Network of Robotic Echelle Spectrographs. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.
31. Thibault, S.; Rabou, P.; Donati, J.F.; Desaulniers, P.; Dallaire, X.; Artigau, E.; Pepe, F.; Micheau, Y.; Vallée, P.; Barrick, G.; et al. CFHT: Spectrograph Optical Design. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy IV, Edinburgh, UK, 26–30 June 2016; Volume 8446.
32. Donati, J.F.; Kouach, D.; Lacombe, M.; Baratchart, S.; Doyon, R.; Delfosse, X.; Artigau, É.; Moutou, C.; Hébrard, G.; Bouchy, F.; et al. SPIRou: A nIR spectropolarimeter/high-precision velocimeter for the CFHT. In Handbook of Exoplanets; Deeg, H.J., Belmonte, J.A., Eds.; Springer: Cham, Swizerland, 2018; ISBN 978-3-319-30648-3.
33. Artigau, É.; Kouach, D.; Donati, J.-F.; Doyon, R.; Delfosse, X.; Baratchart, S.; Lacombe, M.; Moutou, C.; Rabou, P.; Parès, L.P.; et al. SPIRou: The near-infrared spectropolarimeter/high-precision velocimeter for the Canada-France-Hawaii telescope. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy V, Montréal, QC, Canada, 22–26 June 2014; Volume 9147.

34. Oliva, E.; Tozzi, A.; Ferruzzi, D.; Origlia, L.; Hatzes, A.; Follert, R.; Lowinger, T.; Piskunov, N.; Heiter, U.; Lockhart, M.; et al. Concept and optical design of the cross-disperser module for CRIRES. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy V, Montréal, QC, Canada, 22–26 June 2014; Volume 9147.
35. Brucalassi, A.; Dorn, R.J.; Follert, R.; Hatzes, A.; Bristow, P.; Seemann, U.; Cumani, C.; Eschbaumer, S.; Haimerl, A.; Haug, M.; et al. Full System Test and early Preliminary Acceptance Europe results for CRIRES. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.
36. Follert, R.; Taubert, D.; Hollandt, J.; Monte, C.; Oliva, E.; Seemann, U.; Löwinger, T.; Anwand-Heerwart, H.; Schmidt, C.; Dorn, R.J.; et al. Characterizing the cross dispersion reflection gratings of CRIRES. In Proceedings of the Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation II, Edinburgh, UK, 26 June–1 July 2016; Volume 9912.
37. Dorn, R.J.; Follert, R.; Bristow, P.; Cumani, C.; Eschbaumer, S.; Grunhut, J.; Haimerl, A.; Hatzes, A.; Heiter, U.; Hinterschuster, R.; et al. The “ plus “ for CRIRES: Enabling better science at infrared wavelength and high spectral resolution at the ESO VLT. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VI, Edinburgh, UK, 26–30 June 2016; Volume 9908.
38. Baranne, A. Equipement spectrographique du foyer coudé du télescope de 3.60 mètres. Etude de faisabilité d’un spectrographe universel. In Proceedings of the ESO/CERN Conference on Auxiliary Instrumentation for Large Telescopes, Geneva, Switzerland, 2–5 May 1972; pp. 227–239.
39. Schwab, C.; Rakich, A.; Gong, Q.; Mahadevan, S.; Halverson, S.P.; Roy, A.; Terrien, R.C.; Robertson, P.M.; Hearty, F.R.; Levi, E.I.; et al. Design of NEID, an extreme precision Doppler spectrograph for WIYN. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VI, Edinburgh, UK, 26–30 June 2016; Volume 9908.
40. Mueller, M.; Baldwin, D.; Bean, J.; Bergner, H.; Bigelow, B.; Chun, M.Y.; Crane, J.; Foster, J.; Fűrész, G.; Gauron, T.; et al. The Opto-Mechanical Design of the GMT-Consortium Large Earth Finder (G-CLEF). In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.
41. Szentgyorgyi, A.; Baldwin, D.; Barnes, S.; Bean, J.; Ben-Ami, S.; Brennan, P.; Budynkiewicz, J.; Chun, M.Y.; Conroy, C.; Crane, J.D.; et al. The GMT-Consortium Large Earth Finder (G-CLEF): An optical echelle spectrograph for the Giant Magellan Telescope (GMT). In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.
42. Ben-Ami, S.; Crane, J.D.; Evans, I.; Mcmuldroch, S.; Mueller, M.; Podgorski, W.; Szentgyorgyi, A. The optical design of the G-CLEF Spectrograph: The first light instrument for the GMT. In

Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.

43. Pepe, F.A.; Cristiani, S.; Rebolo Lopez, R.; Santos, N.C.; Amorim, A. ESPRESSO: The Echelle spectrograph for rocky exoplanets and stable spectroscopic observations. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy III, San Diego, CA, USA, 27 June–2 July 2010; Volume 7735.
44. Spanò, P.; Mégevand, D.; Herreros, J.M.; Zerbi, F.M.; Cabral, A.; Di Marcantonio, P.; Lovis, C.; Cristiani, S.; Rebolo, R.; Santos, N.; et al. Optical design of the ESPRESSO spectrograph at VLT. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy III, San Diego, CA, USA, 27 June–2 July 2010; Volume 7735.
45. Pepe, F.; Molaro, P.; Cristiani, S.; Rebolo, R.; Santos, N.; Dekker, H.; Mégevand, D.; Zerbi, F.; Cabral, A.; Di Marcantonio, P.; et al. ESPRESSO: The next European exoplanet hunter. Astron. Nachr. 2014, 335, 8–20.
46. Lizon, J.L.; Dekker, H.; Manescau, A.; Megevan, D.; Pepe, F.A.; Riva, M. A large mosaic echelle grating for ESPRESSO spectrograph. In Proceedings of the Optical and Infrared Interferometry and Imaging VI, Austin, TX, USA, 11–15 June 2018; Volume 10701.
47. Pallavicini, R.; Zerbi, F.M.; Spano, P.; Conconi, P.; Mazzoleni, R.; Molinari, E.; Strassmeier, K.G. The ICE spectrograph for PEPSI at the LBT: Preliminary optical design. In Instrument Design & Performance for Optical/infrared Ground-based Telescopes, PTS 1-3; SPIE: Bellingham, DC, USA, 2003; Volume 4841, pp. 1345–1356.
48. Strassmeier, K.G.; Woche, M.; Ilyin, I.; Popow, E.; Bauer, S.-M.; Dionies, F.; Fechner, T.; Weber, M.; Hofmann, A.; Storm, J.; et al. PEPSI: The Potsdam Echelle Polarimetric and Spectroscopic Instrument for the LBT. In Ground-based and Airborne Instrumentation for Astronomy II, PTS 1-4; SPIE: Bellingham, DC, USA, 2008; Volume 7014.
49. Strassmeier, K.; Ilyin, I.; Järvinen, A.; Weber, M.; Woche, M.; Barnes, S.I.; Bauer, S.-M.; Beckert, E.; Bittner, W.; Bredthauer, R.; et al. PEPSI: The high-resolution échelle spectrograph and polarimeter for the Large Binocular Telescope. Astron. Nachr. 2015, 336, 324–361.
50. Strassmeier, K.G.; Ilyin, I.; Weber, M.; Järvinen, A.; Woche, M.; Järvinen, S.; Sablowski, D.; Mallonn, M.; Keles, E.; Carroll, T.; et al. Want a PEPSI? Performance status of the recently commissioned high-resolution spectrograph and polarimeter for the 2 × 8.4 m Large Binocular Telescope. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.
51. Crause, L.A.; Sharples, R.M.; Bramall, D.G.; Schmoll, J.; Clark, P.; Younger, E.J.; Tyas, L.M.; Ryan, S.G.; Brink, J.D.; Strydom, O.J.; et al. Performance of the Southern African Large Telescope (SALT) High Resolution Spectrograph (HRS). In Proceedings of the Ground-Based and

Airborne Instrumentation for Astronomy V, Montréal, QC, Canada, 22–26 June 2014; Volume 9147.

52. Pinto, M.T.; Chanumolu, A.; Quirrenbach, A.; Reffert, S.; Zechmeister, M.; Bauer, F. Physical modeling of echelle spectrographs: The CARMENES case study. In Proceedings of the Modeling, Systems Engineering, and Project Management for Astronomy VIII, Austin, TX, USA, 10–12 June 2018; Volume 10705.
53. Quirrenbach, A.; Amado, P.J.; Ribas, I.; Reiners, A.; Caballero, J.A.; Seifert, W.; Aceituno, J.; Azzaro, M.; Baroch, D.; Barrado, D.; et al. CARMENES: High-resolution spectra and precise radial velocities in the red and infrared. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VII, Austin, TX, USA, 10–14 June 2018; Volume 10702.
54. Seifert, W.; Xu, W.; Stahl, O.; Hagen, H.J.; Carrasco, M.S.; Veredas, G.; Caballero, J.A.; Guardia, J.; Helmling, J.; Hernandez, L.; et al. CARMENES: The VIS channel spectrograph in operation. In Proceedings of the Ground-based and Airborne Instrumentation for Astronomy VI, Edinburgh, UK, 26–30 June 2016; Volume 9908.
55. Tokovinin, A.; Fischer, D.A.; Bonati, M.; Giguere, M.J.; Moore, P.; Schwab, C.; Spronck, J.F.P.; Szymkowiak, A. CHIRON-A Fiber Fed Spectrometer for Precise Radial Velocities. Publ. Astron. Soc. Pac. 2013, 125, 1336–1347.
56. Crane, J.D.; Shectman, S.A.; Butler, R.P.; Thompson, I.B.; Birk, C.; Jones, P.; Burley, G.S. The Carnegie Planet Finder Spectrograph: Integration and commissioning. In Proceedings of the Ground-Based and Airborne Instrumentation for Astronomy III, San Diego, CA, USA, 27 June–2 July 2010; Volume 7735.
57. Wang, X.-L.; Chang, L.; Wang, L.; Ji, H.-X.; Xian, H.; Tang, Z.; Xin, Y.-X.; Wang, C.-J.; He, S.-S.; Zhang, J.-J.; et al. The Coude Echelle Spectrograph for the Lijiang 1.8m telescope. Res. Astron. Astrophys. 2020, 20, 032.

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