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.

Keywords: 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**
South African Astronomical Observatory	**SALT-HRS**	**370–890**	**15,000, 40,000, 65,000**

Observatory	Spectrometer Model	Spectral Range (nm)	Resolution
Lijiang Observatory in China	**CES [57]**	**570–1030**	**37,000**

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