Spectroscopic Observations and Studies of Objects in M31 (Postprint)

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Abstract

The Andromeda Galaxy (M31) is the nearest large spiral galaxy to Earth, similar in structure and comparable in mass to the Milky Way. Spectroscopic observations and studies of M31 objects contribute to understanding the formation and evolutionary history of the Milky Way and galaxies in general. This review compiles relevant spectroscopic observations and research results of objects in M31 by astronomers since the 20th century, covering spectra of more than 5,000 emission-line objects, more than 2,000 star clusters, more than 6,000 stars, more than 1,000 novae, as well as stellar populations in the bulge and disk. Stellar spectroscopic observations have evolved from early studies focusing mainly on supergiants to larger samples and more diverse types in the past two decades, among which red giants have been utilized to investigate the properties and substructures of the M31 galactic disk and halo. Emission-line objects are commonly applied to mass determination of M31, kinematic analysis, and studies of stellar evolution. Research on M31 star clusters concentrates on metallicity and kinematic properties, as well as determining the virial mass of M31 using radial velocities. Studies of the central stellar population of M31 mainly focus on the stellar population composition and kinematic analysis of the nuclear region, with kinematic results more strongly supporting the eccentric disk model of the nuclear region. Finally, we introduce spectroscopic observations of M31 objects and related scientific research conducted with the Guo Shoujing Telescope (LAMOST).

Full Text

Preamble

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Spectroscopic Observations and Studies of Objects in M31

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Abstract

The Andromeda Galaxy (M31) is the nearest large spiral galaxy to Earth, with a structure similar to and mass comparable to the Milky Way. Spectroscopic observations and studies of objects in M31 help us understand the formation and evolution history of the Milky Way and galaxies in general. This paper reviews spectroscopic observations and research results of objects in M31 by astronomers since the 20th century, covering spectra of more than 5,000 emission-line objects, over 2,000 star clusters, more than 6,000 stars, over 1,000 novae, and stellar populations in the bulge and disk. Stellar spectroscopic observations have evolved from focusing on supergiants in early work to larger samples and more types in the past 20 years, with red giants used to study the properties and substructures of M31's disk and halo. Emission-line objects are typically applied to mass determination, kinematic analysis, and stellar evolution studies in M31. Research on M31's star clusters focuses on metallicity and kinematic properties, as well as measuring M31's virial mass using radial velocities. Studies of M31's central stellar populations concentrate on the population composition and kinematic analysis of the nuclear region, with kinematic results more strongly supporting the eccentric disk model for the nucleus. Finally, we introduce spectroscopic observations and related scientific studies of M31 objects by the Guo Shoujing Telescope (LAMOST).

Keywords: spectroscopic observations; M31 (Andromeda Galaxy); kinematics and dynamics; abundances; stellar populations

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1 Introduction

The observable universe contains numerous galaxies, but only several dozen galaxies in the Local Group have resolvable stellar populations that can be studied in detail across multi-dimensional phase space including spatial, velocity, and metallicity dimensions. As the most massive member of the Local Group, M31 is the nearest large spiral galaxy to us. With structural properties similar to the Milky Way, M31 serves as an excellent target for studying galaxy formation and evolution.

Stellar spectra contain a wealth of physical information about celestial objects. With the implementation of numerous spectroscopic observation programs targeting M31 objects in recent years[1-4], the number of spectra obtained for M31 objects has increased dramatically, yielding important scientific results across multiple research directions. These include using spectra for object classification, identifying large numbers of planetary nebulae (PNe)[2, 3, 5], globular clusters (GC)[6-9], supergiants[10-12], and H II regions[13-15] in M31, and using these objects as probes to investigate the dynamical and chemical properties of M31 and to understand its structure, formation, and evolution history[16-20].

This paper reviews spectroscopic observations and research results of objects in M31 from domestic and international studies. The article is structured as follows: Sections 2 and 3 describe spectroscopic observation studies of M31 objects from early work and the past 20 years, respectively; Section 4 specifically introduces spectroscopic observations of M31 objects by China's Guo Shoujing Telescope (Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST)[4]; and Section 5 provides a summary and outlook.

2 Early Spectroscopic Observations and Studies of Objects in M31

In this section, we first review early spectroscopic observations and studies of objects in M31 (up to approximately 2000). M31 is located about 780 kpc from us[21], and some of the brighter objects in the galaxy can be individually resolved and observed spectroscopically. Due to limitations in equipment and observing conditions, early spectroscopic observations of M31 objects were relatively difficult, yielding small numbers of spectra of modest quality. Related research work, such as object identification and galaxy property studies, were in their initial stages, as summarized in Table 1 .

2.1 Stars

Most spectroscopic observations and identifications of stars in M31 begin with photometrically selected candidates, followed by spectroscopic confirmation and spectral classification. In addition to identifying stellar spectral types, spectroscopic analysis also helps determine whether target stars are members of M31.

Due to M31's large distance, only supergiants could be observed spectroscopically in early work. In 1979, Humphreys[22] obtained spectra of 14 supergiant candidates at the Kitt Peak National Observatory (KPNO) 2.1 m and 4 m telescopes, identifying spectral types for 5 supergiants and providing a good supplement to the photometric results of Baade and Swope[23]. Subsequently, they observed 45 red stars from photometric data, obtaining 23 probable M-type red supergiants[24]. Massey[26] used 130 stellar spectra from the KPNO 4 m telescope to test the photometric identification method for red supergiants, finding it to be highly reliable.

Spectroscopic studies of Wolf-Rayet (WR) stars in M31 began in the 1980s, representing a key focus of early giant star identification. WR stars are massive stars with broad emission lines, strong He lines, and weak H lines, classified into WN (nitrogen sequence), WC (carbon sequence), and WO (oxygen emission) types based on their spectra. Moffat and Shara first identified 3 WN stars and 14 WC stars in M31[27] and further analyzed their physical properties[28]. In 1986, Massey et al.[29] identified 4 late-type WC stars and one early-type WN star. In the 1990s, Schild et al. conducted a series of spectroscopic studies using the William Herschel Telescope, performing spectral classification for 6 WR stars from the literature[30] and discovering a new WC4-5 star and a WC7-8 star[31]. In 1999, Greiner et al. also spectroscopically identified a new WR star[32]. These spectroscopic studies found that M31 contains fewer WR stars compared to other Local Group galaxies[29, 33], and they are concentrated in M31's star-forming ring[27, 28, 34].

2.2 Emission-Line Objects

Emission-line objects include PNe, H II regions, and supernova remnants (SNRs). These objects radiate strong ionized gas emission lines, making them easily identifiable through spectroscopic observations. The first large-scale study of M31's kinematic properties was Babcock's 1939 work, which used the double-prism nebular spectrograph on the Lick Observatory Crossley telescope to observe emission-line nebulae in M31's central region[45]. In 1993, Meyssonnier et al.[34] conducted large-scale observations of emission-line objects in M31, producing a catalog of 1,515 emission-line sources, most of which were newly discovered. The catalog consisted primarily of PNe, with a few H II regions and WR stars.

Emission-line objects in M31 serve as important probes for studying M31's kinematic properties and measuring its mass. In 1970, Rubin and Ford[46] obtained spectra of 67 H II regions in M31 at distances of 3-24 kpc and produced the first reliable rotation curve for M31, deriving its mass distribution. H II regions are generally distributed within the galaxy; at larger radii, only neutral gas and low-luminosity stars exist, making optical spectroscopic detection extremely difficult and requiring radial velocity measurements through 21 cm radio spectra of neutral hydrogen. In 1975, Roberts and Whitehurst[47] used this method to extend mass information to 30 kpc. Subsequently, Kent[48] confirmed the compatibility of the two probes.

2.3 Star Clusters

Early identification and research of star clusters in M31 focused primarily on globular clusters (GCs). With high luminosity, integrated spectra of GCs can provide radial velocities, metallicities, and ages for studying M31's kinematic and chemical properties and galaxy history. Early major spectroscopic studies accumulated spectra for over 500 GCs and candidates in M31[35, 36]. Some massive young clusters were also considered GCs in early work.

Using GCs as probes can determine galaxy mass. In 1969, Van den Bergh[37] conducted spectroscopic observations of 44 M31 GCs. Based on these data, Hartwick and Sargent[38] used the virial theorem method to measure M31's mass and further found that metal-poor GCs have larger velocity dispersions than metal-rich GCs. Federici et al.[39] observed 31 new GCs in M31 and, combined with data from Sargent et al.[40] and Battistini et al.[41], estimated M31's projected mass. In 1993, Federici et al.[42] identified 35 GC candidates and obtained radial velocities for 21 confirmed GCs, recalculating M31's projected mass.

Regarding metallicity and color distributions of GCs, early studies found that M31's GC system has similar characteristics to the Milky Way's[35, 36]. Barmby et al.[35] found that M31's GC metallicity distribution is similar to the Milky Way's, with a bimodal structure and a positive correlation between color and metallicity. Two spectroscopic studies of M31's GCs by Huchra et al. indicated that GC metallicity has a weak correlation with projected distance (the projection of an object's distance from M31's center onto the disk plane)[43, 44]. However, Crampton et al.[36] found no correlation between GC color and projected distance in M31.

2.4 Central Stellar Populations of M31

M31 is the second galaxy discovered to host a supermassive black hole, after the Milky Way. Studies of Hubble Space Telescope data reveal that M31's nuclear region has a double-peaked surface brightness structure, with the brighter peak designated P1 and the secondary peak P2[49]. Two theoretical models exist for M31's P1, P2, and central black hole. Emsellem and Combes[50] propose that P1 is a compact star cluster on the verge of tidal disruption by the central black hole, orbiting the black hole at the center of P2. Tremaine[51] suggests that P1 is not a dynamically gravitationally bound system but rather a statistical accumulation of stars orbiting the black hole within P2, with M31's double nucleus actually consisting of an eccentric disk of stars orbiting the black hole.

Spectroscopic studies enable us to understand the kinematic information of the nuclear region and infer the properties of the supermassive black hole. Figure 1 [Figure 1: see original paper] shows the surface brightness and kinematic information of the nuclear region obtained from spectroscopy.

In 1994, Bacon et al. used the integral field spectrograph on the Canada-France-Hawaii Telescope (CFHT) to perform two-dimensional spectroscopic analysis of the nuclear region, finding that M31's nucleus rotates extremely rapidly and that the velocity dispersion peak is offset from the kinematic center[52]. In 1999, Statler et al.[53] used the f/48 Long-slit Spectrograph on the Hubble Space Telescope's Faint Object Camera, finding that the velocity zero point lies between P1 and P2, approximately 0.16 from P2; the peak velocity dispersion (440 km $\cdot$ s^{-1}) is located on the extension line between P1-P2, about 0.06 from P2. Statler et al. used these data to evaluate the two models above, finding that Tremaine's model[51] better matches the data if the mass of the central black hole in the model is increased by 10%. Kormendy and Bender[54] used CFHT's Subarcsecond Imaging Spectrograph (SIS) to obtain integral field unit (IFU) spectra of M31's nuclear stellar population, calculating the kinematic characteristics and metallicities of nuclear region stars and deriving a non-parametric radial velocity distribution and an estimate of the central black hole mass. The mass result is consistent with Tremaine's model[51], again confirming M31's eccentric disk model.

3 Spectroscopic Observations and Studies of Objects in M31 in the Past 20 Years

With the updating and development of telescope instrumentation, spectroscopic observations and studies of objects in M31 have made substantial progress in the past 20 years (approximately after 2000). Table 2 summarizes the related research work.

3.1 Stars

Compared with the 20th century, the number and variety of stars in M31 observed spectroscopically have grown rapidly in the past 20 years: large numbers of red giants and massive main-sequence stars have been observed, and supergiant sample sizes have also increased substantially beyond earlier work.

3.1.1 Red Giants Red giants are widely used to study the dynamics, substructure, and accretion history of galactic halos. However, due to their low luminosity, early telescopes were insufficient to obtain spectra of red giants. Even to date, most spectroscopic observations of red giants rely on large telescopes like Keck, using the Low Resolution Imaging Spectrometer (LRIS) on Keck I and the DEep Imaging Multi-Object Spectrograph (DEIMOS) on Keck II. LRIS spectra are obtained in red and blue arms, covering a combined wavelength range of 3,200-10,000 Å with a slit length of 8 . DEIMOS, built later than LRIS, has substantially improved performance in all aspects. DEIMOS can cover a wavelength range of 5,000 Å in a single exposure with high resolution (R 6,000), a slit length of 16.6 , and can obtain multi-slit spectra.

Based on LRIS on Keck I, Reitzel and Guhathakurta[1, 55] published infrared spectra of 14 halo red giant candidates at 19 kpc from M31's center, measuring their radial velocities and distinguishing M31 halo stars from Milky Way foreground stars using the equivalent width of the Ca II triplet in the spectra. Guhathakurta et al.[56, 57] increased the sample of spectroscopically observed red giant candidates in M31 to 99, finding that M31's halo stellar density is an order of magnitude higher than the Milky Way's. Based on 29 red giant spectra from Keck observations, Reitzel et al. found that M31 halo red giants have higher metallicities than Milky Way halo red giants, and that the metallicity distribution of M31 halo red giants is similar to those of M31 GCs, Milky

Way GCs, and Local Group dwarf galaxies. Four red giants in the sample have particularly strong Ca II triplet lines, appearing in velocity-metallicity phase space as possible disk stars or metal-rich tidal debris from accretion events[58]. Reitzel et al. also conducted spectroscopic observations and studies of red giant samples near the well-known M31 globular cluster G1, finding a wide metallicity distribution range for red giants in the sample ($-2.8 <$ [Fe/H] < 0.0 dex). Metal-poor red giants ([Fe/H] < -1 dex) have a broad velocity distribution ($-500 < \mathrm{v} < 50\ \mathrm{km \cdot s^{-1}}$), while metal-rich red giants ([Fe/H] -0.7 dex) have more concentrated velocities (approximately $-480\ \mathrm{km \cdot s^{-1}}$). Six red giants in the sample that are kinematically associated with G1 may be tidal debris from G1, with one possibly belonging to G1[59].

Based on DEIMOS on Keck II, the Guhathakurta group proposed the SPLASH (Spectroscopic Landscape of Andromeda's Stellar Halo) project targeting red giants in M31's halo and disk. Photometric observations primarily used the Mosaic camera on the KPNO 4 m telescope, imaging in broadband M and T2 filters and narrowband DDO51 filter. Spectroscopic observations used DEIMOS on Keck II, and by 2017 had obtained over 20,000 stellar spectra of M31's disk, halo, and dwarf galaxies in 170 fields, with projected distances of 2-230 kpc[60]. Some of the spectroscopic and photometric fields are shown in Figure 2 [Figure 2: see original paper].

The primary goal of SPLASH is to study halo dynamics by mapping the metallicity distribution and structure/substructure of M31's disk and halo, as well as merger-produced debris trails[16, 61], and to investigate the kinematics, metallicities, and masses of M31's satellite galaxies[62-65]. In 2006, Guhathakurta et al.[61] released preliminary SPLASH results, first identifying 68 red giants in M31; Guhathakurta et al. used these to estimate the radial velocity and metallicity of M31's giant south stream (GSS[66]). Analysis of non-GSS red giants indicated low halo metallicities and possible new substructures[61]. Based on SPLASH data, Kalirai et al.[67] proposed a new method to separate M31 red giants from Milky Way foreground dwarf stars, identifying 530 red giants at projected distances of 12-165 kpc from M31's center. As the SPLASH project progressed, the observed area increased annually, and the number of red giant spectra obtained also increased[16-18, 68-70]. By 2018, the SPLASH project had identified over 5,000 red giants in 50 regions of M31[71].

Based on SPLASH data, scientists have made a series of new discoveries in studying M31's disk and bulge kinematics, M31 halo substructures, and the chemodynamical properties of the halo. Dorman et al.[17] found that the spheroidal component within 20 kpc of M31's center has high stellar density and high metallicity, suggesting that M31 within 20 kpc is more like an elliptical galaxy than a typical spiral galaxy bulge. Kalirai et al.[72] found that the radial velocity distribution of red giants at 20 kpc from M31's center is bimodal. Collins et al.[69] found that M31's thick disk is more metal-poor than the thin disk and kinematically lags behind the thin disk. Ibata et al.[73] discovered a low-luminosity, inhomogeneous disk-like structure comprising about 10% of M31's total disk luminosity with a wide metallicity range. In studies of M31's halo substructure, a blue, metal-poor arc-like substructure was discovered along M31's northwest major axis, possibly part of a stellar stream originating from NGC 205[74]; and a kinematically cold stellar population was found on M31's southeast minor axis, likely originating from tidal debris of the GSS[75]. Additionally, Ibata et al. found that M32, NGC 205, and the GSS have clear kinematic correlations[76]. Gilbert et al. found that M31's halo surface brightness distribution follows a power law with index -2.2 ± 0.2[70], and that velocity dispersion gradually decreases with projected radius but not substantially[71]. M31's halo exhibits a weak metallicity gradient[18, 67], consistent with a galaxy formation model of gradual chemical growth of M31's halo[67]. Compared to field stars in M31's halo, member stars of various substructures have higher metallicities[16].

3.1.2 Massive Stars Luminous blue variables (LBVs) are in the late evolutionary stages of massive stars, with extremely high brightness, making them important objects for studying the evolution of very massive stars. In 2007, Massey et al.[108] used the WIYN 3.5 m telescope to identify 12 new LBV candidates in M31. In 2016, Massey et al.[109] performed spectral classification for 1,895 stars in M31 and M33, identifying 9 LBV candidates and one new WR star. Sarkisyan et al. conducted further spectroscopic observations and studies of two LBV candidates from the Massey et al.[108, 109] sample (J004341.84+411112.0[110, 111] and J004526.62+415006.3[110]), confirming both stars as LBVs. In 2014, Humphreys et al. analyzed spectral features of 82 stars from the Massey et al.[108] sample, finding 3 new LBV candidates and 3 new post-red supergiant candidates. They also found that M31 LBVs in the sample, unlike most other variable and bright stars, do not have hot circumstellar dust, and LBVs have lower wind velocities compared to B-type supergiants and Of/WN stars[113]. Spectra of confirmed LBVs all lack [O I] emission lines, while some LBVs exhibit [Fe II] emission lines[114].

OB-type stars are massive stars with spectral types O and B, mostly distributed in loosely structured OB associations.

In 2001, Smartt et al.[115] obtained high-quality spectral data for two massive stars in M31's OB 10 association (OB 10-64, B0 Ia and OB 10-WR1, WC6) and performed detailed quantitative analysis, providing abundances of He, C, Ni and other elements along with stellar parameters. This was the first atmospheric chemical analysis study of M31 B-type stars and WR stars. In 2008, Cordiner et al.[10] conducted low-resolution spectroscopic observations and studies of two supergiants near M31's OB 78 association (MAG 63885 and MAG 70817), detecting diffuse interstellar bands (DIBs) in circumstellar gas of M31 OB stars. In 2011, they obtained spectra of 34 B-type stars in M31, deriving spectral classifications, radial velocities, and interstellar reddening parameters for these stars. Based on these spectral data, they detected 11 DIB features in M31[10].

The number of identified WR stars and their spectral data in M31 continue to increase. In 2012, Neugent et al.[116] conducted a large-scale search and spectroscopic identification of WR stars in M31, discovering 107 new WR stars, bringing the total number of spectroscopically confirmed WR stars in M31 to 154. Most of the WR stars from this observation are WN and WC types, with a WC/WN ratio lower than previous studies. Sander et al.[117] used Neugent et al.'s data to analyze all 17 known late-type WN stars at the time, finding that all stars have luminosities between 10^5 L and 10^6 L , and that single-star evolution-formed late-type WN stars have initial mass ranges of 20-60 M . In 2016, Shara et al.[118] identified the first WN/C transition-type WR star in M31, finding that this WN/C star is surrounded by an emission-line nebula.

Yellow supergiants are massive stars with spectral types F or G. According to stellar evolution models, most stars briefly pass through the yellow supergiant phase when evolving from the OB main sequence to the red supergiant stage, making yellow supergiants quite rare. Drout et al.[11] used the Hectospec spectrograph on the MMT telescope to select 54 yellow supergiants and 62 candidate yellow supergiants in M31, finding that yellow supergiants' positions in the Hertzsprung-Russell diagram are consistent with evolution models, but finding no stars more massive than 25 M , inconsistent with models. Gordon et al.[12] selected a sample of yellow supergiants from the Local Group Galaxy Survey (LGGS) project and Humphreys et al.'s 2014 study[113], obtaining spectroscopic data for 113 yellow supergiants and two new hypergiants in M31. They estimated initial masses for these giants and found that over half of the observed sample is ejecting circumstellar dust.

3.1.3 Novae Novae are phenomena where thermonuclear reactions run away on white dwarfs accreting from companion stars. Since the 20th century, astronomers have discovered over a thousand novae in M31, some of which have been observed with low-resolution spectroscopy. Novae can be divided into classical novae (CNe), which erupt only once (such as M31N 2015-01a), and recurrent novae (RNe), which erupt multiple times (such as M31N 2008-12a). M31N 2015-01a is a luminous red nova (LRN) discovered in M31 in January 2015, and its spectroscopic observations provide valuable samples for LRN research[119, 120]. Williams et al.[119] and Kurtenkov et al.[120] conducted spectroscopic observations, finding that M31N 2015-01a has strong Hα emission lines that are gradually weakening, and the nova's color is becoming redder. Kurtenkov et al. measured a radial velocity from the nova's Hα line that matches the rotational velocity of objects at that location very well[120]. M31N 2008-12a is a rapid recurrent nova (RRN) that first erupted in 2008, the fastest recurrent RNe system known and a candidate progenitor for Type Ia supernovae. From 2008 to 2017, nine eruptions were observed with a period of about 1 year. Spectroscopic evidence indicates that its eruptions are highly asymmetric, possibly with jets directed toward the observer. High-resolution spectroscopic analysis reveals that this nova contains no Ne and has low O content, suggesting the system's white dwarf may be a C-O white dwarf[121-123].

3.2 Emission-Line Objects

3.2.1 Planetary Nebulae Planetary nebulae (PNe) are emission-line nebulae formed when envelope gas is ejected from low- to intermediate-mass stars at the end of their evolution, widely distributed in galaxies and commonly used as probes for studying galaxy dynamics. PNe spectra have strong [O III] emission lines at approximately 5,007 Å. PNe are typically detected by first identifying them in wide-field narrowband [O III] images, then using multi-object spectrographs to measure their velocities[77-80]. Hurley-Keller et al. used this method to study and obtain kinematic information for 135 PNe in M31[82], most of which are located outside M31's bulge, with 5 PNe showing velocities suggesting they may belong to a tidal stream in M31's outer halo.

In 2002, the William Herschel Telescope commissioned the Planetary Nebula Spectrograph (PN.S), which can identify PNe and obtain their radial velocities in a single spectroscopic analysis, more efficient than traditional methods[3, 83]. Halliday et al.[2] published accurate velocities for 723 PNe in M31's bulge and disk from PN.S. Based on PN.S observations, Merrett et al.[3] published a catalog containing 3,300 emission-line objects, including positions, magnitudes, and velocities, as shown in Figure 3 [Figure 3: see original paper]. These objects are distributed in a disk with radius of 1.5°, and its rotation curve in the outer region is consistent with previous rotation curves based on neutral hydrogen observations.

Due to high spectral quality and large sample size, the catalogs published by Merrett et al. and Halliday et al. have been widely applied to studies of object identification, kinematics, and chemical properties of M31. For example, they have been used to verify the precision of other emission-line object identification methods[84, 85], measure M31's mass and dark matter distribution, study star formation evolution and metallicity distribution[5, 86, 87], investigate the physical properties of emission-line objects themselves in M31[88], and establish new emission-line object catalogs[13].

In addition to dynamical studies, galaxy PNe systems can also be used for planetary nebula luminosity function (PNLF) studies. The PNLF is an important standard candle for measuring extragalactic distances. Due to M31's proximity to the Milky Way and the large number of PNe samples observed in M31, M31's PNe system is an excellent target for studying extragalactic PNLF, particularly the bright-end cutoff of the function. Kwitter et al.[87] and Galera-Rosillo et al.[5] re-observed deep spectra for a small number of PNe from Merrett et al.'s catalog, studying the bright-end cutoff of the PNLF in M31's disk. Galera-Rosillo et al. suggest that PNe at the bright-end cutoff of M31's PNLF originate from stars of about 1.5 M , while Kwitter et al. suggest this value is about 2 M .

PNe are also important stages in stellar evolution, and detailed metallicity analysis helps us understand nucleosynthesis and dredge-up mixing processes experienced by low- and intermediate-mass stars. Since 2013, based on the Optical System for Imaging and Low-Intermediate-Resolution Integrated Spectroscopy

(OSIRIS) on the Gran Telescopio Canarias (GTC), astronomers have successively observed high-quality spectra of 27 planetary nebulae in the outer regions of M31[5, 89-91], with a resolution of 0.63 nm. Based on GTC spectra, detailed metallicities of PNe can be measured. Fang et al., based on the metallicity distribution of these PNe, suggest that the Northern Spur and GSS may share a common origin, and that PNe in M31's halo may have formed in the progenitor galaxy of the GSS or formed in the metal-rich gas of M31's outer disk before migrating to the halo[91-93].

3.2.2 Other Emission-Line Objects Emission-line objects also include H II regions and SNRs, which are less numerous than PNe and are generally published as byproducts in emission-line object catalogs along with PNe. In 2006, Merrett et al.[3] published a catalog containing 3,300 emission-line objects in M31. In 2012, Sanders et al.[13] used the Hectospec multi-fiber spectrograph on the MMT to obtain spectra of 253 H II regions and 407 PNe in M31. In 2017, Martin et al.[94] used CFHT observations to establish a radial velocity catalog of nearly 800 emission-line point sources. Martin et al.'s catalog includes about 450 newly discovered emission-line objects, among which is a new SNR candidate.

3.3 Star Clusters

In the past 20 years, the number of identified star clusters in M31 has grown daily[6, 19, 95-97]. Perrett et al.[19] used the WYFFOS spectrograph on the William Herschel Telescope to obtain medium- to low-resolution spectra of over 200 GCs in M31. Galleti et al. identified 118 new GCs through a series of observations[6, 95, 96]. Kim et al.[97] obtained spectral types and radial velocities for 748 candidates and identified 113 new GCs. Caldwell et al. used the Hectospec spectrograph on the MMT to observe nearly 1,000 objects, of which 670 are possible star clusters[98]. In addition, smaller-sample spectroscopic observations are gradually increasing[8, 99]. Veljanoski et al. observed a sample of 53 GCs and performed the first kinematic analysis of far outer halo GCs[100, 101]. Fan et al. used the OMR spectrograph (Optomechanics Research Inc.) on the 2.16 m telescope at the Xinglong Observatory of the National Astronomical Observatories to observe spectra of 19 confirmed M31 GCs and performed kinematic analysis[8, 99]. Star clusters are generally divided into GCs and open clusters, with GCs being old, massive clusters and open clusters being young, low-mass clusters. In recent years, astronomers have discovered a class of massive and young clusters in the Milky Way and nearby galaxies, named young massive clusters (YMCs)[102]. Caldwell et al.[98] identified 140 YMCs in M31 and analyzed their ages and reddening based on spectroscopic data.

The metallicity distribution of a galaxy's GC system reflects the galaxy's early formation history and the origins of different types of clusters. Spectroscopic studies of M31's GC system have found that M31's GC metallicity bimodal distribution is not as pronounced as the Milky Way's[6, 19, 99]. Some researchers believe that M31's distribution differs from the Milky Way's bimodal distribution and may be a more complex structure[6, 7, 103-105].

A comparison of GC metallicity distributions between M31 and the Milky Way is shown in Figure 4 [Figure 4: see original paper]. Caldwell et al.[7] suggest a broad peak centered at [Fe/H] = -1 with three secondary peaks. Chen et al.[105] and Galleti et al.[6] consider a single Gaussian distribution unlikely, and Galleti et al.[6] find that a three-peak model fits better. The metallicity gradient of M31's outer halo clusters is not significant. For GCs older than 7 Gyr, there is a trend that older GCs have lower metallicities.

Perrett et al.[19] found that the average metallicity of M31's GC system is similar to the Milky Way's, while Galleti et al.[6] suggest that M31 has a larger fraction of metal-rich GCs. In spatial distribution and kinematics, metal-rich GCs tend to be concentrated toward M31's center and may be a kinematically distinct subsystem. The velocity distribution of young clusters matches the disk's rotation curve well and also correlates well with the kinematics of H II regions, confirming the spatial connection between young clusters and the star-forming disk[6, 19, 98, 99]. The velocity dispersion of outer halo GCs decreases with projected distance, similar to halo stars, and can be described by a power law with index -0.5[100, 101].

In terms of metallicity and kinematics, the rotation pattern of M31's metal-rich and intermediate-metallicity GCs is similar to M31's neutral hydrogen, while metal-poor GCs have larger velocity dispersions[6]. Unlike the Milky Way, M31 has numerous very bright GCs in its distant outer halo[96]. Mackey et al. found that halo-related GC populations and substructure-related GC populations have perpendicular rotation patterns, interpreted as originating from two accretion events possibly separated by billions of years[106]. Using GCs as probes, dynamical masses obtained through tracer mass estimation and other methods are $1.2–1.6 \times 10^{12}$ M [100, 101].

In addition to medium- and low-resolution spectra, Sakari and Wallerstein[9] and Larsen et al.[107] also performed medium- to high-resolution spectroscopic observations of M31 GCs, measuring different metallicities for 25 and 12 GCs in M31, respectively, and compared them with the Milky Way and nearby galaxies to explore M31's early formation history.

3.4 Central and Bulge Stellar Populations of M31

Early spectroscopic observations and studies discovered M31's nuclear double-peaked structure (P1, P2). In 2001, Bacon et al.[124] used spectroscopic observations to find that M31's nuclear kinematic axis almost coincides with the major axis but not with the P1-P2 axis, and that the velocity distribution along the P1-P2 axis is asymmetric, suggesting that the high nuclear velocities may be related to P2. In 2005, Bender et al.[125] published red and blue spectra of M31's nuclear region obtained with Hubble's imaging spectrograph. They detected a tiny kinematic component P3 near P2, with velocity dispersion inconsistent with both P1 and P2, where the supermassive black hole is likely located. Population analysis indicates that P1 and P2 are primarily composed of old red giants, while P3 consists of young A-type main-sequence stars or giants. Saglia et al., using slit spectroscopy data from the Hobby-Eberly Telescope (HET), inferred that there may be an ionization source similar to an active galactic nucleus near M31's center, and that M31 may have undergone a gas-rich minor merger about 100 Myr ago, causing gas counter-rotation on the minor axis and other nuclear activity[126, 127].

M31's bulge is considered a composite bulge, possessing both a classical bulge (CB) and a boxy-peanut bulge (B/P). Saglia et al.[127], based on integrated spectra of bulge populations obtained by Opitsch et al.[128], inferred that most stars in the CB formed along with the primordial galactic disk, which on larger scales would evolve into a bar and further buckle into a B/P shape. Zieleniewski et al., using spectroscopic observations from the Palomar Observatory 5.08 m telescope, found that in M31's bulge outer region, the stellar population is old (>12 Gyr), with metallicities near solar and slight α-element enhancement, and a [Na/Fe] gradient of about 0.3 dex[129].

In regions near M31's center, integrated spectroscopy of stellar populations reveals younger populations (4-8 Gyr) with metallicities rising to 3 times solar[126, 127] and a Na enhancement gradient of about 1.0 dex[129].

In 2018, Li et al.[14] used the WIYN 3.5 m telescope to obtain spectra of 77 PNe candidates located within about 500 pc of M31's center, 49 of which (approximately 64%) were first-time spectroscopic observations. Li et al. obtained spectra of 267 PNe and 33 H II regions in M31's central and bulge regions. The calculated radial velocities reveal the rotation pattern of the inner bulge, consistent with the kinematic pattern of the disk's minor axis. Li et al. also derived the bulge mass within 340 pc of M31.

4 Spectroscopic Observations and Studies of M31 Objects by LAMOST

Most of the spectroscopic observations and research work on M31 objects described above are based on data from foreign telescopes. For a long time, due to the small aperture of domestic optical telescopes, it was difficult to conduct spectroscopic observations and studies of objects in M31. The Guo Shoujing Telescope (also known as the Large Sky Area Multi-Object Fiber Spectroscopic Telescope, LAMOST[4]) is China's first major astronomical facility. Located at the Xinglong Observatory, LAMOST is a new type of telescope with a wide field of view (5°) and large aperture (effective aperture 4 m) that can simultaneously obtain spectra of 4,000 objects. Figure 5 [Figure 5: see original paper] shows examples of spectra for several types of objects observed by LAMOST. LAMOST entered its scientific survey phase in 2011. The LAMOST Spectroscopic Survey of the Galactic Anti-center (LSS-GAC[130]) in the survey covers the vicinity of M31 and M33 and is currently China's only systematic spectroscopic observation program for M31 objects. This section introduces LAMOST's spectroscopic observations and studies of M31 objects.

LAMOST's extremely high spectral acquisition efficiency provides important assistance for discovering and identifying new objects in M31. As early as the LAMOST commissioning phase, Yuan et al.[131] reported 36 observed PNe candidates, 17 of which were newly discovered. Chen et al.[132] identified and confirmed 5 GCs and 23 GC candidates in M31 and M33. In 2020, Zhang et al.[15] published a catalog of 3,305 Hα emission-line point sources in the M31 and M33 fields based on LAMOST data, including 24 newly discovered PNe candidates, 19 H II region candidates, 10 SNR candidates, and 1 symbiotic star candidate. Wang et al.[104] obtained age and metallicity information for 346 star clusters. Huang et al.[133] identified a new LBV in M31 from the LAMOST database: LAMOST J0037+4016. This star is a low-luminosity LBV, the 7th LBV discovered in M31. Its location differs from the previous six, situated in an extended substructure at the outermost part of M31's disk, currently the most distant LBV from M31's center.

Using LAMOST spectroscopic data, Zou et al.[20] studied the stellar population properties of M31's bulge and disk and M31's kinematic properties. They found that the radial velocity dispersion of stellar populations in M31 decreases with distance, with stars in the bulge being kinematically hotter. Age studies show that M31's bulge formed about 12 Gyr ago, while the disk is relatively young. The galaxy's overall average metallicity is near solar, with a very weak abundance gradient. Wang et al. found that old star clusters in M31 have metallicity peaks at [Fe/H] -0.6 and -1.5 dex, consistent with previous studies[6, 7]; but many clusters also exist at [Fe/H] -1 dex, indicating a more complex structure. Chen et al.[105] measured ages, metallicities, and masses for 305 star clusters in M31 based on LAMOST data, with 46 YMCs and 260 GCs in the sample. These clusters have masses between 10^3 and 10^7 M , YMC metallicities [Fe/H] similar to solar, distances of 7-17 kpc, and GC metallicities [Fe/H] peaking at about 0.7 dex.

5 Summary and Outlook

With the gradual development of spectroscopic observation technology and the commissioning of large telescopes and modern spectroscopic instruments, the number of spectroscopically identified objects in M31 has grown daily. Currently, we have obtained over 5,000 emission-line objects in M31, including H II regions and PNe plus a few SNRs; over 2,000 star clusters, mostly GCs including more than 100 YMCs; over 6,000 stars, including more than 5,000 red giants plus other giants, OB-type stars, and over 100 WR stars, as well as 7 discovered LBVs; over 1,000 novae; and spectra of stellar populations in M31's nucleus and disk.

Using these spectroscopic data, astronomers have conducted chemical abundance evolution analysis and kinematic studies of M31. For example, they have found that M31's GC system has slightly higher metallicity than the Milky Way's[44, 55] and that its metallicity bimodal distribution differs slightly from the Milky Way's GC metallicity distribution, indicating different formation histories for the star cluster systems of M31 and the Milky Way[7, 104]. M31's halo shows a weak metallicity gradient, suggesting it formed through the accretion of small stellar systems[19, 20, 39, 42, 44, 58]. Based on kinematic information, M31's dynamical mass and mass distribution have been measured. Different probes have revealed rotational differences among various galaxy components. Kinematic studies of the halo region have discovered kinematically cold substructures rich in M31's halo, such as the GSS, Northern Spur, and Southeast Shelf.

Although considerable results have been achieved in spectroscopic observations of M31, many characteristics remain to be explored. Looking to the future, LAMOST's Phase II plan will use Lenghu in Qinghai as its new site, with further equipment upgrades that will increase the limiting magnitude by 2 mag and greatly expand the survey scale. The Chinese Survey Space Telescope (CSST), planned for launch in 2023, will be equipped with a slitless spectrograph capable of spectroscopic observations in three bands: GU (0.255-0.4 m), GV (0.4-0.6 m), and GI (0.6-1.0 m), with a limiting magnitude expected to reach 22-23 mag. The planned MUltiplexed Survey Telescope (MUST) also intends to conduct large-scale deep multi-object spectroscopic surveys. In addition, other international spectroscopic survey projects such as the Sloan Digital Sky Survey-V (SDSS-V), the William Herschel Telescope Enhanced Area Velocity Explorer Instrument (WEAVE), the Subaru Prime Focus Spectrograph (PFS) on the Subaru Telescope, and the Maunakea Spectroscopic Explorer (MSE) on CFHT will all focus on spectroscopic observations and studies of M31 objects. The launched James Webb Space Telescope (JWST) carries the Near InfraRed Spectrograph (NIRSpec), capable of obtaining spectra of 100 objects simultaneously. The planned Thirty Meter Telescope (TMT) and the 40 m-class European Extremely Large Telescope (E-ELT) will greatly expand spectroscopic observation capabilities for M31 objects when constructed, making samples for studying M31 more complete. Astronomers look forward to presenting M31's various detailed features more clearly and accurately to better understand the formation and evolution of spiral galaxies.

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