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A NEW CHALLENGE IN THE STUDY OF YOUNG STARS: MASSIVE HBE STARS

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In a short review paper, it is discussed the main spectral and photometric features of young intermediate-and high mass stars. Based on the results of research in this area over the past two decades, have presented the features of massive Herbig Be stars, and the main problems and tasks of researches for understanding the physics and evolution of these stars are noted.

Keywords: Stars: pre-main sequence – star formation – massive Ae/Be Herbig stars – protoplanetary disks – stellar evolution

1. CURRENT STATE OF RESEARCHES

It is known that the vast majority of stars of various masses visible in the optical range at the Pre-Main Sequence (PMS) stage of their evolution are surrounded by circumstellar disks [18]. In such disks, flow - accretion of matter to the star surface continues [9, 64, 66]. At the same time, a strong stellar wind is observed in young stars along with accretion. T Tauri stars (T Tauri stars - TTS) with masses of 0.5-2.0 $M_{\odot}$ are classified according to their spectra, especially according to the intensity of the Hα emission line. In addition, in the spectral energy distribution of those stars, a strong excess of radiation in the UV, near and far IR range is detected [24, 41]. TTSs with Hα line equivalent width (EW) larger than or equal to 10 Å are called as classical TTS (CTTS), and stars with EW Hα less than 10 Å are called weak TTS (WTTS) [5, 61]. The more massive (2-10 $M_{\odot}$) analogs of CTTS stars are called as Herbig Ae/Be (HAe/Be) [30] type stars. It was later shown that the line width measured at 10% of the Hα line intensity (Hα 10%) and the Hα profile measured in the high-resolution spec-

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trum are more sensitive for diagnosing the accretion process [35]. Non-accreting objects with (ΔV $\leq 230 - 270$ km/sec) have a symmetric chromospheric origin profile. However, very wide asymmetric profiles are observed in accreting objects (ΔV $\geq 230 - 270$ km/s) [42, 80].

HAe/Be stars show strong emission lines in their spectra and a strong emission excess in the IR range of the spectrum, which is associated with dust emission [18, 70]. In such stars, the spectrum radiated by the circumstellar disk mixes with the atmospheric spectrum of the central star, resulting in a combined spectrum. The selection and study of spectral lines with a circumstellar disk from this spectrum can provide information about the physical processes occurring in the disk and the interaction between the central star and the disk. Such an interaction mechanism in lowmass CTTS stars is relatively well studied, because these stars have dipole-shaped magnetic fields with an intensity of 1kGs. Based on this, magnetospheric accretion models were developed [9]. According to this model, the magnetic field intersects the circumstellar disk, and the pressure of the material flowing from above balances the pressure of the magnetic field created by the stellar surface. The matter spilled in the scattering radius is poured into the stellar surface at ballistic speed along the tubes of the magnetic field lines. Such a model allows to explain the changing activity of radiation lines observed in the spectrum of CTTS stars, the formation of UV radiation excess, and the nature of the additional continuum created in the spectrum, which veils the absorption lines in the UV and optical ranges. The issue of explaining the activity of HAe/Be-type stars with the magnetospheric accretion model has not yet been confirmed. Measurements of magnetic fields in HAe/Be stars have shown that the global magnetic fields of these stars are on the order of 100 Gs [1, 2, 33, 34]. Unlike cold stars, in HAe/Be-type stars, energy is transported away from the center of the star not by convection, but by radiation [23, 35, 57]. confirmed that the formation of the magnetosphere accretion process in the HAe/Betype stars may occur even at a 100 Gs magnetic field.

As we mentioned above, recently HAe/Be stars are divided into two subgroups: these are HAe and HBe types [64]. In recent years, the study of HAe type subgroup stars has shown that such stars have signs of magnetospheric accretion. For example, [12] studied the profile of the He I λ1083 & line in 50HAe/Be stars and showed that, while no signs of accretion were observed in hot HBe-type stars, signs of accretion were clearly detected in relatively cold HBe and all HAe stars. However, the expected radius of the magnetosphere in such stars is smaller than that of CTTS stars and is located closer to the stellar surface.

As mentioned, the mechanism of activity of HAe stars can be explained in the magnetospheric accretion model by choosing different parameters. However, the number of such studies on HBe-type stars is very few. Both types of stars have been studied for different small groups by different authors. A serious turn in these studies began only after the operation of the Gaia mission [21, 46, 77]. In these works, according to the more accurate parallax values provided in the Gaia DR2 archive, 252 HAe/Be-type stars were located on the HR diagram, and thus their ages and masses were determined based on theoretical tracks.

Meeus et al [52] studied the energy distribution of 14 intermediate-mass Ae/Be Herbig-type stars in the IR and sub-mm regions and showed that a great diversity is found in the energy distribution of these stars. Dust particles rich in carbon and others rich in oxygen have been observed in some stellar disks. The authors showed that two main groups of spectral distributions were detected. The IR and sub-mm spectrum of group 1 stars can be described as a function of thermal radiation and the power of a cold body. This radiation can be provided by an optically thick geometrically thin disk and cold body radiation. In group 2 stars, a large amount of cold dust is observed in the near-IR region, regardless of the amount of excess energy radiated. In addition, amorphous and crystalline silicate bands were found in the observed disks.

In recent years, new information about the upper limit of the masses of HAe/Be-type stars has been discovered. In particular, as a result of the spectral and photometric observations of the extra-atmosphere space mission Gaia, conducted by the European Space Agency in 2013, it has been revealed that the upper limit of the masses of HAe/Be stars can be up to 40M⊙. Based on these observations, [27, 77]added the list of such stars to the list of the other 200 known classical HAe/Be stars.

2. NEW DATA AND UPCOMING CHALLENGES

Knowledge of the upper mass limit of the higher-mass stars that harbor the HAe/Be phenomenon is not well defined. Such massive stars include various groups of young objects (Young Stellar Objects-YSO). Until recently, 255 well-studied and confirmed HAe/Be stars were known [70]. The recent work on the study of these stars can be found in these works [27, 77]. The lower mass limit consists of a mixture of cooler HAe/Be and TTS stars, which has not been rigorously defined in the scientific literature [10, 59, 73, 74].

Objects above the mass limit of $M_* > 8 - 10\ M_\odot$ are called (massive) MYSO. It should be noted here that the difference between the previous HAe and HBe types and MYSO is not an unequivocal determination, but in many cases, it is determined by the visibility conditions of the object. An extensive list of MYSO objects can be found in [49] work. At present, extensive information about MYSO has been extensively described in the works of [19, 44]. Although several hundred objects are listed in these works, their extensive research has not been carried out, and their characteristics have not yet been fully studied.

Currently, by Guzmán-Díaz et al [27], a virtual catalog containing data of 318 stars was created (http://svo2.cab.inta-csic.es/projects/harchibe/docs/ ?pagename=The_Archive). In that catalog, the mass of more than 40 stars was estimated in the range of $10-40M_{\odot}$. This result in itself opens up a new area for research in the study of HAe/Be stars. Thus, until recently, it was considered that the upper limit of the mass of HAe/Be stars that retain the characteristics of this type is 12 $M_{\odot}$ [11,13,70]. Since the number of HAe/Be stars is still much smaller than the number of low-mass TTS stars, of which there are more than a thousand known, many of their properties are relatively poorly understood. Moreover, since most of such stars are fainter than V $\sim$ 13 mag, their spectral observation requires telescopes with apertures of at least 2 m and larger. Such difficulties have not allowed the extensive study of massive young stars so far.

Later [6] determined the physical parameters for 131 HAe/Be stars based on homogeneous results. The most prominent of such works is [79]. This paper not only presented the spectroscopically determined masses, luminosities, surface gravities, and ages from the distances given in the Gaia DR2 archive, but also added these refinements for a large number of stars in the northern sky. These studies showed that the existing characteristics of HAe/Be stars are heterogeneous and can be divided into two parts. The first part is HAe stars, whose ages and masses are $t > 3$ million years, and whose masses are in the range of $M_* \sim 2-3M_{\odot}$. HBe type stars are younger, but their masses are larger: $t < 3$ million years, $M^* > 3M_{\odot}$. The deficit of older HBe stars indicates that such protostars reach the main sequence earlier, i.e. the dissipation of their circumstellar disks ends much earlier.

Estimation of disk-to-stellar accretion in HAe/Be stars is by modeling the UV radiation excess of a large number of stars [17,54,79], or by correlation of spectral emission lines [6,79]. Information about the more distant parts of the disc can be diagnosed mainly by means of spectral energy distribution (SED) [31,52]. The SED curves of different objects depend on the geometry of the disc, the change type as in UX Ori, the presence of accretionary matter and accreting dust particles in the disc, and the amount of gas and dust in the disc.

As we mentioned above, magnetic fields are not generated in high-mass HBe stars. Therefore, there is no reason to apply the magnetospheric accretion model [53]. Recent studies have shown that the most massive star showing signs of accretion had a mass of 4 $M_{\odot}$ [26,79]. In addition, as we move from intermediate to high mass, they behave very differently than low-mass stars. In massive stars that produce strong UV radiation, photoevaporation is stronger, resulting in large gaps (cuts) in the disk [45]. As a result of chemical and shock evolution, the formation of planets in the disc may occur more rapidly [55]. In addition, certain structures are found in more massive stellar disks. For example, spiral structures in the disk are mainly observed in hotter stars [22]. Therefore, it is assumed that giant planets should form mainly in high-mass stars [71]. However, the details of these processes have not yet been clarified. Therefore, the study of massive young stars is an important tool for understanding the evolution of their disk and the formation of planets.

Shamakhy Astrophysical Observatory has been a long time conducting spectral and photometric studies of low, intermediate and high-mass stars with the participation of the Ismailov N.Z. and coauthors. Especially HD179218, AB Aur, IL Cep, and other stars of the medium and large mass HAe/Be type were extensively studied, and the activity observed in the emission spectrum and the physical properties of these stars were extensively studied [36,37,39,40]. In this direction, the SED curves of 56 stars located in the Orion OB2 starformation region in the range of $0.26 - 100\mu$m were constructed, the IR radiation excess around them was estimated, and the fundamental parameters of these stars were determined. Among such stars, characteristic signs of HBe stars have been detected, especially in the spectrum of high-mass stars of the B spectral classes [39].

Recently, the evaluation of the mass of dust in disks in various regions of star formation with ages of 1-5 million years has shown that the mass of dust in disks as a whole decreases with increasing age [14, 14, 25, 72]. The typical dissipation time of protoplanetary disks is 3 million years [50, 65]. According to modern ideas, the dissipation (breakup) of discs occurs due to the following mechanisms: 1) accretion of matter from the disc to the stellar surface [28], 2) scattering of disc material by the wind [28] , 3) the process of particle accretion and planet formation within the disk [56,68]. In addition, factors such as external photoevaporation and dynamical interactions can have a significant impact on the evolution of disks [81]. Studying the characteristics of stars selected from star formation regions of different ages would allow us to clarify which of these factors play an important role in disc dissipation at different ages.

To conduct a proper study of massive young stars, first of all, a variety of objects covering a large range of masses and ages must be selected. Spectral and photometric observations of such stars should be conducted and spectral energy distribution curves should be studied. Spectral observations will allow studying the change of profiles in Hα and Hβ lines, the structure of the radiation component, and thus check the spatial structure of the circumstellar disk and the detection of accretion signs. Carrying out photometric observations in different broadband filters will allow us to study the photometric characteristics of the interstellar medium and the nature of the disk radiation and to determine the fundamental parameters. Studying the SED curves of the program stars will allow us to give an idea about the amount of gas and dust in the disk by studying the energy excess.

Guzmán-Díaz et al. [27]constructed the SED curves of 209 Herbig Ae/Be-type stars using the results of broadband photometric observations and studied the characteristics of the circumstellar disks. The temperature, luminosity, radius, mass, and age of each star were determined. It is shown that the masses of the stars take values in the range of 2-12 $M_{\odot}$. The authors show that there is no correlation between the shape of transition disks and the SED curves, and 28% of stars have transition disks. Gaps detected in transition disks are more frequent in HBe stars than in HAe stars. It has been shown that photoevaporation in these sources does not play a decisive role in disc dissipation.

Testi et al [69] studied the parameters of stars in different young star complexes and showed that the mass, luminosity, accretion rate, and disk mass of the stars in the L1688 cluster of the youngest ρ Oph region, ~ 1 million years old, taken in the neighborhood of the Sun, are similar to those taken from other regions, are not distinguished of the parameters. The age interval with other star clusters was 0.55 million years. In such clusters, the accretion rate is inversely proportional to the age of the stars. The age dependence of the mass of dust in the disk shows a more complex character.

Young stellar disks show radiation excess due to absorption of photospheric radiation by the central star and reradiation mainly in the near and far-IR region [82]. Furthermore, another source of radiative excess is the energy generated during disc accretion [28, 43]. If the gas-dust disc has fragmented, we should not observe accretion signatures, such as ultraviolet (UV) emission excesses and broad wing profiles in the Hα line.

It is known that within a few million years of their initial formation, small and medium-mass young stars acquire a circumstellar disk and a magnetic field. The magnetic field formed in the deep convective zone and outer mantle creates expanding cold spots on the stellar surface, hot zones, additional radiation excess in the chromosphere and corona, activity similar to solar activity [24,60,61]. Since the rapid study of exoplanets and the confirmation of the existence of planets in most stars in the Galaxy, the study of disks around young stars has generated great interest.

Studies of the Solar System and many young stellar disks have shown that planet formation in the circumstellar disks of nascent stars occurs within several million years of formation [63]. It is now widely accepted that planets form in the disks of young stars that are the product of star formation [67]. In many modern instrument complexes, for example, in the near-infrared (IR) and optical ranges [8], the millimeter Atacama Large Millimeter/submillimeter Array (ALMA) complex has obtained images of the disk around young stars. In the ALMA complex, several hundred a.u. away from the disk, various disk structures - rings, voids, asymmetric structures caused by the interaction of giant planets were discovered [3, 47, 48]. SPHERE images have shown disc shadows, rings, spiral arms, dips, and fissures in the outer disk at distances of 20-200 a.u. [7]. The nature of such phenomena in massive young stars remains unexplored.

Recent studies have shown that remnant dust disks are currently detected around some very old stars (β Pic, α Lyr) [51]. This indicates that the process of creating planets in those stars has come to an end. Spectral energy distribution curves of such stars constructed in a wide wavelength range show that, compared to normal stars, the radiation excess in these stars manifests itself only in the far infrared (IR) range $\lambda \geq 10\mu$m [16]. After the observations of the Infrared Astronomical Satellite (IRAS) mission, it was found that on average only 21% of the stars have Vegatype features, and these features show some dependence with the spectral class. The frequency of encountering protoplanetary disks around young stars is higher, but the direction of change of the amount of dust in such disks at different ages remains unstudied.

A study of the SED curves of a group of stars in the OB1 star cluster located in the Orion Nebula showed that, although this star cluster is considered a young star-forming complex, Vega-type features are also observed around some of the stars located here [39,40]. These results show that the evolution period of circumstellar disks depends on the age of the stars, their mass, spectral class, possibly chemical composition, etc., and depend on other factors. It is of great importance to investigate which mechanisms are more important during evolution in changing the amount of gas and dust that make up the disk matter.

3. DISCUSSION

Finally, let us mention the following important issues about the evolution of medium- and large-mass protoplanetary disks that are still waiting for their investigation. For example, how does the amount and composition of gas in protoplanetary disks change during evolution? High-resolution Hα spectral observations can unambiguously reveal whether gas accretion is present in the disc. If there is accretion, the disk is rich in gas. However, the lack of accretion does not mean that the disk is low on gas. The accretion rate may vary and may be faint at the time of observation. In addition, accretion may be reduced in the observed disk due to photoevaporation and dynamical interactions.

In general, the evolution of the amount of gas (in other words, the ratio of gas to dust by amount) is currently the most important problem for protoplanetary disks. The amount of gas is an important factor for both the formation of giant planets and the formation of Earth-group planets, because the gas affects the dynamics of the formed dust particles and ensures the formation of rocky blocks.

Although some models assume the gas-to-dust ratio to be 100 , as in the interstellar medium, this is clearly not the case. On the one hand, photoevaporation should reduce the amount of gas. On the other hand, as the particles become planetesimals and planets, the gas to dust ratio must increase . At the end of the initial disc dissipation process, the disc should consist of dusty compounds combined with gas. But the evolution of gas and dust can be more complex than monotonically decreasing. Therefore, it is necessary to take into account that the gas-dust ratio is much more than 100 at the initial stage [32,62,78]. It seems that the mass of the central star should also play an important role in the dissipation process.

The proposed scientific research task is devoted to one of the most important fields of modern astrophysics - the study of the physical properties of disks formed around massive young stars during the formation and initial evolution of stars (1-100 million years). One of the interesting directions of research in this issue is the study of the physical properties of protoplanetary disks formed around young stars using photometric observation material conducted in a wide wavelength range.

Thus, based on the summary given above, it is clear that the study of the characteristics of the circumstellar disks of a statistically significant number of massive stars with different ages and masses is of great importance to determine the process of planet formation and the role of various mechanisms in the protoplanetary disks of such stars and to understand the dissipation process of young stellar disks as a whole. The proposed scientific research task envisages conducting research in this direction.

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