

Studying Complex Star-Forming Fields: Rosette Nebula and Monoceros Loop

Chris Hathaway and **Anthony Kuchera**, co-authors

Dr. Nadia Kaltcheva, Physics and Astronomy, faculty adviser

Christopher Hathaway obtained a B.S. in physics in 2007 and is currently pursuing his masters in physics education at UW Oshkosh. He collaborated with Dr. Nadia Kaltcheva on his senior research project and presented their findings at the American Astronomical Society meeting (2008), the Celebration of Scholarship at UW Oshkosh (2009), and the National Conference on Undergraduate Research in La Crosse, Wisconsin (2009).

Anthony Kuchera graduated from UW Oshkosh in May 2008 with a B.S. in physics. He collaborated with Dr. Kaltcheva from fall 2006 through graduation. He presented his astronomy-related research at Posters in the Rotunda (2007 and 2008), the Wisconsin Space Conference (2007), the UW System Symposium for Undergraduate Research and Creative Activity (2007 and 2008), and the American Astronomical Society's 211th meeting (2008). In December 2009 he earned an M.S. in physics from Florida State University where he is currently working toward a Ph.D. in experimental nuclear physics.

Dr. Nadia Kaltcheva is a professor of physics and astronomy. She received her Ph.D. from the University of Sofia in Bulgaria. She joined the UW Oshkosh Physics and Astronomy Department in 2001. Her research interests are in the field of stellar photometry and its application to the study of Galactic star-forming fields and the spiral structure of the Milky Way.

Abstract

An investigation that presents a new analysis of the structure of the Northern Monoceros field was recently completed at the Department of Physics and Astronomy at UW Oshkosh. Northern Monoceros is arguably the most complex star-forming region in the Perseus section of the Milky Way. The area harbors a huge collection of recently born massive stars. It also contains some of the most spectacular features of interstellar matter known to date.

The method of investigation chosen for this study is called $uvby\beta$ photometry. This is a sophisticated astronomical technique that enables the derivation of stellar physical parameters with high precision. The photometry-derived quantities were used to obtain reliable homogeneous distances to groups and layers of stars located toward Monoceros. Our study provides an updated working model of the central part of the field up to a distance of 6500 light years and also gives us a better understanding of its overall properties. This survey has laid the basis to further investigate the connection between the young stellar population in Monoceros and its associated interstellar material in order to cast light on some aspects of star formation.

Significance of the Monoceros Star-forming Field

One of the major, most extensively studied star-forming fields in our Galaxy is found toward the constellation Monoceros. It is located in the Northern sky, lies toward the outer parts of the Galaxy, and is thought to be part of the Perseus spiral arm of the Milky Way. It is one of the least obscured by interstellar dust regions in the Galactic plane, thus offering excellent observational opportunities to study star formation at a large distance.

Monoceros is rich in massive, recently born stars, found both in compact stellar clusters and loose, gravitationally unbound stellar associations. Based on previous investigations, it seems that it has a complex structure with several groups and layers projected along the line of sight. The area is dominated by the Rosette Nebula—a large low-density cloud of glowing ionized hydrogen in which star formation has recently taken place. The young massive stars recently formed within Rosette emit vast amounts of ultraviolet light, ionizing and heating the gas surrounding them. The Rosette Nebula is located near one end of a giant molecular cloud (Rosette Molecular Cloud)—a place of ongoing star formation. The Monoceros Loop (a circular optical nebulosity in the vicinity of the Rosette Nebula) is thought to be a supernova remnant (the final product of the evolution of a very massive star).

Rosette Nebula and the Monoceros Loop are thought to be spatially connected to the stars of the large Mon OB2 association (Ruprecht 1966)—an extended loose group of massive, recently born stars. About 5° north of Rosette, the young open cluster NGC 2264 and the more compact Mon OB1 association seem to be spatially connected to the diffuse Cone Nebula (Herbst 1980). The positional coincidence of stars of the Mon OB2 association with the Monoceros Loop suggests that the star formation in this region was induced or sped up by the passage of a supernova shock wave through the clumpy interstellar medium (Singh and Narayan 1979). Such triggering of star formation is a key idea in the contemporary star-formation theory leading astronomers to constantly look for observational evidence. Star formation appears to be clumped into a hierarchy of structures, from small stellar clusters to giant star-forming complexes. The interplay between gravity and supersonic turbulence is a critical factor in this process. The formation of stars is closely linked to the properties of their parental clouds of interstellar matter. The spatial distribution of the members of an embedded cluster or association may hold important clues about the formation mechanism and initial conditions in the parental molecular cloud. On the other hand, once formed, the young massive stars (known as OB stars) may play a constructive or a destructive role in the process of star formation. Even a single OB star has a profound influence on the surrounding interstellar matter. Its radiation and energetic wind could evaporate nearby clouds and terminate the star-forming processes. Alternatively, the radiation pressure from an OB star may also prompt the collapse of the molecular cloud which otherwise may not contract spontaneously. Such a triggering process may act over a very large distance, implying possible self-sustaining formation of stars.

In light of the growing importance of Northern Monoceros in the study of star formation, precise distances to the apparent structures of young stars in the field are important for a variety of reasons. Reliable distances allow us to pinpoint the precise location of the clusters and associations, thereby allowing us to better understand the star-forming history of the region. Precise distances also allow us to better understand

their connection and influence on the surrounding interstellar gas and dust, thus shedding light on the process of triggered formation of new stars for this particular field.

Method

Studying the Galactic star-forming fields is a complex experiment. These fields are the building blocks of the Milky Way's spiral arms. Because the Sun is positioned deep inside the Milky Way, the Galactic spiral arms look strung out to us along the line of sight, leading to superposition and mixing of star-forming fields in the sky. To uncover the structure of the star-forming fields, the distances to the OB stars have to be determined and the locations mapped. The OB stars are short-lived (20 million years) objects of a highly peculiar nature and are thus difficult to study. However, the structure and overall characteristics of the Galactic star-forming fields are entirely based on distance determinations of such stars.

Stellar distance is the most important parameter in astronomy. It is also the most difficult one to obtain. The direct method to find stellar distances is the method of stellar parallax, based on the revolution of the Earth around the Sun. Unfortunately, from the surface of the Earth, parallaxes of stars located even in the nearest star-forming fields cannot be obtained—the stars are too far away and parallaxes cannot be measured. Other approaches are the indirect photometric and spectroscopic methods, where the stellar light is measured and used to obtain physical stellar parameters (such as temperature, total energy emitted, etc.) that can yield stellar distance. The most widely used photometries are the UBV and uvby β systems. The uvby β photometry provides precise distances, but observations are needed in six intermediate-band filters. This makes the task more difficult to achieve. The UBV photometry is easier to obtain, but the precision in the distances it yields is not always sufficient. In both systems, calibrations need to be established based on stars with direct (parallax) distances. Recently, using data from space (ESA 1997), it was possible to test these calibrations and establish which of them are reliable (Kaltcheva and Knude 1998; Wegner 2007; Kaltcheva and Makarov 2007).

Our Study

Here we present a thorough photometric investigation of Northern Monoceros utilizing uvby β data. The field we studied (12° by 12°) is centered on the Rosette Nebula. We used all recently born stars with uvby β photometric data presently available through astronomical databases (Hauck and Mermilliod 1998; Kaltcheva, Olsen, and Clausen 1999). Our sample was at least 90% complete for stars brighter than 9.2 magnitudes and allowed us to delineate the structure of the central part of the field up to a distance of 6500 light years (2000 pc). The parsec, or pc, was our chosen unit of distance throughout this study and is equivalent to how far light travels in 3.26 years.

Results

In the overall photometric investigation of star-forming fields, several consecutive steps were performed. First, data were collated for as many OB stars as possible. Then, based on this data, the influence of the interstellar dust on the light from the

stars was estimated and corrected to obtain the true stellar colors. From this point the field could be studied via photometric diagrams, which cast light on the stellar content of the field in general. The true stellar colors brought information about stellar physics and provides (via calibrations, based on well-studied samples of nearby stars) stellar temperature, chemical composition, age, and, most importantly, intrinsic stellar brightness. A comparison of the intrinsic stellar brightness to apparent brightness allowed us to obtain the stellar distance. Having the distance, together with the stellar coordinates, allowed the structure of the field under investigation to be mapped in two and three dimensions.

From the uvby β photometric data we calculated precise distances and estimations of the extinction of stellar light due to the interstellar dust for the stars included in our sample. These parameters made it possible to reveal various groups of stars within the field of study.

The Monoceros OB2 Association

The stars in our sample are dominated by the Mon OB2 association. This association has been extensively studied by a number of authors and is considered to cover a large area of the sky toward the Rosette Nebula and Monoceros Loop. This area also contains a large number of young open clusters. The extensive investigation by Turner (1976) concluded that three groups of stars of differing ages are present in this association. The stars of the open cluster NGC 2244, as well as most stars in the Rosette Nebula, make up the youngest group, while the oldest stars are found mostly at the periphery of the association. Turner listed 48 stars as members of the Mon OB2 association and, based on spectroscopic calibrations and UBV photometry, derived the distance of 1590 pc, which is the currently accepted distance to this association. Most of the stars previously assigned to Mon OB2 were included in our sample. Based on the precise photometric distances for the individual stars we derived, we found that these stars are spread out between 1 and 3 kpc (1 kpc = 1000 pc). We suggest that they do not belong to a single OB association, which is expected to be more compact in terms of distances to individual stars.

We investigated how stars of different intrinsic brightness are distributed across the field. The intrinsic brightness is a measure of the total amount of energy produced by a star per unit time. We found that the intrinsically bright stars are restricted between a Galactic latitude of -3° and 1° . We conclude that two groups of massive stars were present in our sample: a compact group of 12 stars at a distance of 1.26 kpc located toward the Monoceros Loop and a layer spread out between 1.5 and 3 kpc. When projected in the sky, the massive stars of the layer are spread all over the field, indicating a large apparent depth of this star-forming region.

OB associations can also be detected kinematically as their internal velocity dispersion is usually small. To further confirm our findings, we searched the astronomical databases for radial velocity measurements. We found that most of the stars at 1.26 kpc had radial velocity measurements with a mean value of 26.3 km/s and a standard deviation of 9.8 km/s—just slightly larger than the radial velocity dispersion limit for an OB association (Mathieu 1986). Thus, the available radial velocities support the existence of a compact group of young stars at 1.26 kpc spatially correlated with the Monoceros Loop and Rosette Nebula.

The Open Clusters NGC 2264 and NGC 2244

Open clusters are compact groups of stars that often form within the boundaries of the OB associations. NGC 2244 and NGC 2264 are the most prominent clusters spatially connected to Mon OB2 and Mon OB1, respectively. Due to a high number of peculiar and binary stars and an additional complication of high, non-uniform extinction in Northern Monoceros, the study of these clusters has been difficult and the distances existing in the literature for NGC 2264 and NGC 2244 have varied substantially (Peréz, Thé, and Westerlund 1987).

Our sample included the brightest stars in both clusters, and we presented the first distance estimations for them based on photometric uvby β data. We found indications that, within the errors of the survey, the range in the derived photometric distances was larger than the expected range for compact groups. Thus, subgroups were separated within the clusters. Additional inspection of the photometric diagrams related to stellar physical parameters indicated that the stellar content of the possible subgroups is similar. At the same time, the photometric diagrams related to stellar distance further supported the notion of subgroups at different distances. This finding of subgroups within the clusters, however, requires further confirmation. The photometric distances can be strongly affected by a variety of factors: unresolved binaries, peculiar interstellar extinction, stellar emission, and inhomogeneous photometric data. Because of this, we also provided distance estimates to NGC 2264 and NGC 2244, treating them as groups of stars at the same distance. Our estimates of 833 ± 38 pc and 1585 ± 323 pc, respectively, agree very well with the median value of the distances to these clusters existing in the literature to this point.

Conclusions

Precise uvby β stellar distances and reddening have been obtained for a sample of 209 recently born stars in a $12^\circ \times 12^\circ$ field in Northern Monoceros. The photometry-derived parameters allowed us to obtain homogeneous distances to groups and layers of stars in this field out to a distance of 2 kpc. We presented new distance estimates for the young open clusters NGC 2244 and NGC 2264 and suggested a presence of possible subgroups in both of them. Our work did not reveal the classical Mon OB2 at 1.6 kpc. We suggested that a relatively compact group of massive stars at 1.26 kpc can be distinguished close to NGC 2244 and spatially correlated with the Monoceros Loop and Rosette Nebula. This finding is supported by radial velocity measurements found in the literature. A layer of massive stars between 1.5 and 3 kpc can also be detected, averaging a distance of approximately 2.15 kpc. Our results provide the basis to further investigate the connection between the prominent stellar groupings and the structures of interstellar matter for this important star-forming region.

Acknowledgements

Support for this research was provided by the National Science Foundation grant AST-0708950. N.K. acknowledges support from the SNC Endowed Professorship. A Wisconsin Space Grant Consortium undergraduate research award (A.K.) and two Wisconsin Space Grant Consortium scholarships (A.K. and C.H.) are also acknowledged. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

This research was recently published (Kaltcheva, Kuchera, and Hathaway 2010) in the refereed international journal *Astronomische Nachrichten* (Wiley InterScience). Some preliminary results were published in the *Proceedings of the Wisconsin Space Conference* (Kuchera, Kaltcheva, and Hathaway 2007).

Bibliography

- European Space Agency (ESA). The Hipparcos and Tycho Catalogues. *European Space Agency SP-1200* (1997): 1–17.
- Hauck, B., and M. Mermilliod. “uvby β Photoelectric Photometric Catalogue.” *Astronomy and Astrophysics Supplement Series* 129 (1998): 431–33.
- Herbst, William. “Recent Results on Associations—Anatomy of CMa OB1 and MON OB1.” *International Astronomical Union Symposium* 85 (1980): 33–45.
- Kaltcheva, Nadia T., and Jens Knude. “A Test of B-type Star H β Photometric Distances via the HIPPARCOS Parallaxes.” *Astronomy and Astrophysics* 337 (1998): 178–82.
- Kaltcheva, Nadia T., Anthony N. Kuchera, and Christopher Hathaway. “A uvby β Photometric Analysis of the Monoceros Star-forming Field.” *Astronomische Nachrichten* 331, no. 4 (2010): 384–96.
- Kaltcheva, Nadia T., and Valeri V. Makarov. “The Structure and the Distance of Collinder 121 from *Hipparcos* and Photometry: Resolving the Discrepancy.” *Astrophysical Journal* 667 (2007): L155–57.
- Kaltcheva, Nadia T., Erik H. Olsen, and Jens-Viggo Clausen. “Strömgren and H β Photometry of O and B Type Stars in Star-forming Regions. II. Monoceros OB2, Canis Major OB1, and Collinder 121.” *Astronomy and Astrophysics* 352 (1999): 605–8.
- Kuchera, Anthony N., Nadia T. Kaltcheva, and Christopher Hathaway. Paper presented at lecture, 17th Annual Wisconsin Space Conference, (UW Superior, August 16–17, 2007).
- Mathieu, Robert D. “The dynamical evolution of young clusters and associations.” *Highlights of Astronomy* 7 (1986): 481–88.
- Peréz, M. R., P. S. Thé, and B. E. Westerlund. “On the Distances to the Young Open Clusters NGC 2244 and NGC 2264.” *Publications of the Astronomical Society of the Pacific* 99 (1987): 1050–66.
- Ruprecht, J. *Trans. International Astronomical Union* 12B (1966): 350.

- Singh, K. P., and S. Narayan. "Evidence for Supernova-induced Star Formation in the Monoceros OB2 Association." *Astrophysics and Space Science* 66 (1979): 191–99.
- Turner, David G. "The Value of R in Monoceros." *Astrophysical Journal* 210 (1976): 65–75.
- Wegner, W. "Absolute Magnitudes of OB and B Stars Based on *Hipparcos* Parallaxes." *Monthly Notices of the Royal Astronomical Society* 374 (2007): 1549–56.