Massive Stars Near and Far
Proceedings IAU Symposium No. 361, 2024
J. Mackey, J. S. Vink, & N. St-Louis, eds.
doi:10.1017/S1743921322002526

Metallicity Dependences of Massive Star Formation from Theoretical and Observational Perspectives

K. E. I. Tanaka[1,2], **Y. Zhang**[3], **T. Shimonishi**[4] **and R. Matsukoba**[5]

[1]University of Colorado Boulder, Boulder, CO 80309, USA
email: `kei.tanaka@colorado.edu`

[2]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

[3]University of Virginia, Charlottesville, VA 22904-4325, USA

[4]Niigata University, Ikarashi-ninocho 8050, Nishi-ku, Niigata, 950-2181, Japan

[5]Kyoto University, Sakyo, Kyoto 606-8502, Japan

Abstract. Massive stars play crucial roles in astrophysical settings across cosmic history, and thus it is a fundamental problem to understand whether their formation processes are universal or diverse in various galactic environments. In particular, metallicity is the essential characteristic of cosmic evolution. Our theoretical studies have suggested some degrees of metallicity dependence of massive star formation. In the extremely metal-poor case of $< 10^{-2}\,Z_\odot$, protostellar disks are significantly unstable, and the photoionization feedback is more efficient. We also execute an ALMA survey targeting massive protostars in the Large Magellanic Clouds (LMC) with $0.5\,Z_\odot$. We found that the outflow properties of LMC protostars (mass, momentum, energy) are consistent with those of Galactic protostars, suggesting the universality of massive star formation at least in the range of ~ 0.5–$1\,Z_\odot$.

Keywords. stars: formation, (stars:) binaries (including multiple): close, (galaxies:) Magellanic Clouds

1. Introduction

Massive stars play pivotal roles in various fields of astrophysics. They are the sources of UV radiation, turbulent energy, and heavy elements in galaxies. Close binaries of massive stars are likely progenitors of gravitational wave binaries. Moreover, from a theoretical perspective, the first stars formed just after the big bang, known as Population III stars, are predicted to be very massive as ~ 10–$100\,M_\odot$. Because of the importance of massive stars across cosmic history, It is fundamental to understand whether their formation processes are universal or diverse in various environments across galactic evolution. In particular, metallicity is the key environmental parameter as it increases with cosmic time. We conduct theoretical and observational studies to investigate the potential metallicity dependences in massive star formation near and far.

2. Theoretical modeling

Various dynamical processes control the star formation efficiency (SFE) from the initial cloud core with ~ 0.1 pc (Rosen et al. 2020). Protostellar feedback and disk fragmentation are particularly important to determine the initial mass of each newborn star.

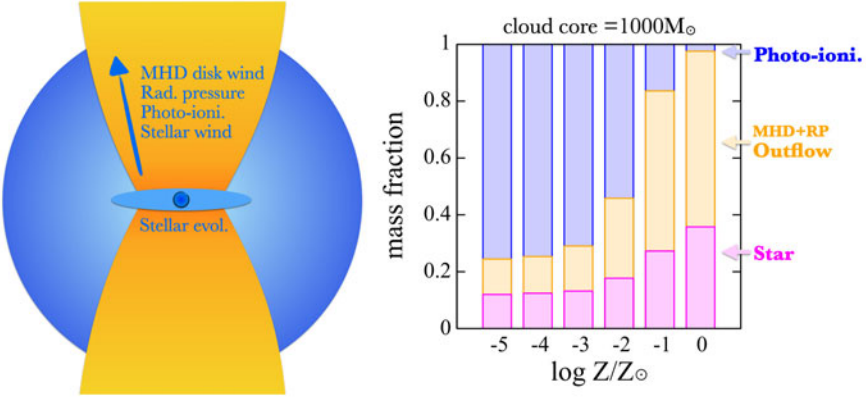

Figure 1. The semi-analytic model of multiple feedback in massive star formation (Tanaka et al. 2017; 2018). *left*: The schematic picture of the feedback model. We take into account MHD disk winds, radiation pressure, and photo-ionization, and investigate their metallicity dependences. *right*: A typical result from the model calculations, showing the mass fractions of the stars (pink), outflows (yellow), and photo-ionized gas (blue) in the case started from massive cloud cores of 1000 $M_\odot$. The photo-ionization feedback becomes dominant feedback at the lower metallicity of $\lesssim 10^{-2}\, Z_\odot$.

2.1. *Multiple feedback processes*

In the formation of Galactic low-mass protostars, it is well-known that the magnetically-driven disk winds is the dominant feedback (Machida & Hosokawa 2013). Radiation pressure acting on dusty gas was regarded as the crucial feedback in present-day massive star formation for a long time (Krumholz et al. 2009). In the formation of Population III stars from primordial gas, photo-ionization is suggested to be the main feedback (McKee & Tan 2008). Classically, these multiple feedback processes were investigated independently. We developed a semi-analytic model of massive star formation including multiple feedback processes, i.e., MHD disk winds, radiation pressure, and photo-ionization, over the wide range of metallicity (left panel of Figure 1, Tanaka et al. 2017; 2018). Our model suggested that, MHD disk wind is the dominant feedback at solar metallicity, rather than radiation pressure even in the formation of very-massive stars over 100 $M_\odot$. In this sense, in the Galactic environment, massive star formation can be considered as the scaled-up version of low-mass star formation. On the other hand, photo-ionization becomes more significant as the metallicity decreases, reducing the SFE compared to the solar-metallicity case, because photo-ionization is more efficient in the absence of dust grain (right panel of Figure 1). The same metallicity dependence of radiative feedback was also found in radiative hydrodynamical simulations by Fukushima et al. (2020). In recent years, multi-feedback have been investigated with radiative MHD simulations by various groups (e.g., Commerçon et al. 2022, Rosen 2022), but the number of theoretical works that take into account the metallicity is still limitted.

2.2. *Disk stability and fragmentation*

In our Galaxy, most of massive stars have close companions (Sana et al. 2012). Low-metallicity massive close-binaries are likely the progenitors of gravitational wave binaries (Abbott et al. 2019). Such massive close-binaries would form by gravitational fragmentation of unstable disks. We developed an analytic disk model in massive star formation, and investigated the metallicity dependences of disk stability (left panel of Figure 2, Tanaka & Omukai 2014). The massive protostellar disk is typically (marginally) unstable

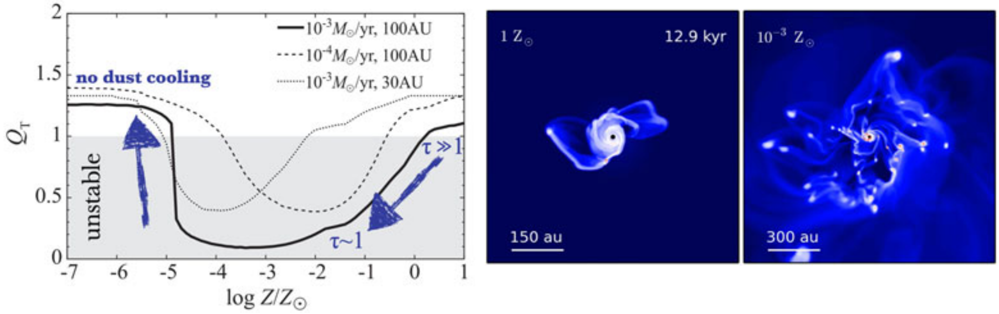

Figure 2. Metallicity dependence of disk stability in massive star formation. *left*: The analytic model of disk stability with various metallicity (Tanaka & Omukai 2014). The disk is predicted to be significantly unstable at the metallicity range of $\sim 10^{-2}$–10^{-5} $Z_\odot$. *right*: Radiative hydrodynamical simulations of protostellar disks at metallicity of 1 and 10^{-3} $Z_\odot$ (Appendix C of Matsukoba et al. 2022). As predicted by the analytic model (the right panel), the disk is more unstable at the low-metallicity case.

with the Toomre's parameter $Q \sim 1$ at the solar metallicity. The disk becomes even more unstable as the metallicity decreases from $Z_\odot$, because the disk optical structure changes from a very optically thick to a thinner (easy-to-cool) regime. The Toomre parameter Q becomes as small as ~ 0.1 at $\sim 10^{-2}$–10^{-4} $Z_\odot$. Such an unstable disk cannot hold its disk structure, and catastrophic fragmentation could occur and form a small stellar cluster. The disk is more stable at the extremely metal-poor case of $\lesssim 10^{-5}$ $Z_\odot$ since the dust cooling does not work effectively. We also conduct radiative hydrodynamical simulations to investigate dynamical evolution of protostellar disks at various metallicities, which agree well with the analytic prediction, i.e., massive protostellar disks are more unstable at 10^{-3} $Z_\odot$ than $Z_\odot$ (right panel of Figure 2 Matsukoba et al. 2022). This metallicity dependence of disk stability may explain the higher close-binary fraction at lower metallicity reported by Moe et al. (2019).

3. ALMA observation

Observational studies of massive star formation have made significant progress in recent years due to improvements in observational techniques. So far, observational studies of massive star formation are mostly limited in the Galactic environments of $\sim Z_\odot$. However, thanks to the high-resolution and high-sensitivity of ALMA, people start to detect protostellar outflows with sub-pc scales in the the Large Magellanic Cloud (e.g., Fukui et al. 2015, Shimonishi et al. 2016). The Large and Small Magellanic Clouds (LMC and SMC) are the excellent laboratory to investigate low-metallicity star formation with ~ 0.5 and $0.2\,Z_\odot$, respectively. Here we conducted a new ALMA survey project, called "MAGellanic Outflow and chemistry Survey (MAGOS)", in which we target 40 massive protostars in the LMC and SMC (K. Tanaka et al., in prep.). As a first science case with the MAGOS data, we investigated the physical properties of molecular outflows of 30 LMC protostars (left panel of Figure 3). We found that the masses, momenta, and energies of LMC outflows are correlated with their protostellar luminosities. These correlations are basically consistent with the well-known Galactic outflow properties (e.g., Beuther et al. 2002, Maud et al. 2015) (see right panel of Figure 3). This similarity could suggest protostellar outflows, i.e., the guideposts of MHD disk accretion at the small scale, have relatively universal properties at the metallicity range of ~ 0.5–$1\,Z_\odot$. Further ALMA studies will observationally examine the universality of massive star formation at various metallicities.

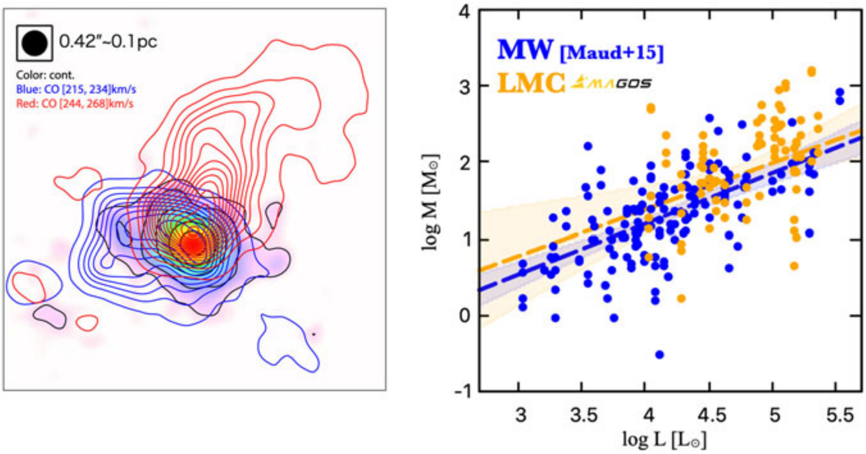

Figure 3. Protostellar outflows in the LMC from our MAGOS project (K. Tanaka et al., in prep.). *left*: An example of bipolar CO outflows detected. *right*: The outflow masses versus the protostellar luminosities of the LMC outflows (orange, MAGOS) and the Galactic outflows (blue, Maud et al. 2015). The LMC outflow properties are reasonably consistent with the Galactic counterparts.

4. Summary

Massive stars are important objects in cosmic time, and thus we investigate their formation at various metallicity from theoretical and observational perspective. Our theoretical models show that star formation dynamics could be qualitatively different in very low-metallicity environments of $\lesssim 10^{-2}\,Z_\odot$. At such a low-metallicity, the protostellar feedback is dominated by photo-ionization, and the protostellar disk becomes significantly unstable forming a small stellar cluster. We also conduct a new ALMA survey project called MAGOS, targeting low-metallicity protostars in the LMC and SMC. The LMC outflow properties (mass, momentum, and energy) are similar to those of the Galactic counterparts, possibly suggesting the universality of massive star formation dynamics at the metallicity range of ~ 0.5–$1\,Z_\odot$. Further studies from theoretical and observational perspectives are required to understand the universality and diversity of massive star formation.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019, ApJL, 882, L24
Beuther, H., Schilke, P., Menten, K. M., et al. 2002, Hot Star Workshop III: The Earliest Phases of Massive Star Birth, 267, 341
Commerçon, B., González, M., Mignon-Risse, R., et al. 2022, A&A, 658, A52
Fukui, Y., Harada, R., Tokuda, K., et al. 2015, ApJL, 807, L4
Fukushima, H., Hosokawa, T., Chiaki, G., et al. 2020, MNRAS, 497, 829
Krumholz, M. R., Klein, R. I., McKee, C. F., et al. 2009, *Science*, 323, 754
Machida, M. N. & Hosokawa, T. 2013, MNRAS, 431, 1719
Matsukoba, R., Tanaka, K. E. I., Omukai, K., et al. 2022, arXiv:2206.03497
Maud, L. T., Lumsden, S. L., Moore, T. J. T., et al. 2015, MNRAS, 452, 637
McKee, C. F. & Tan, J. C. 2008, ApJ, 681, 771
Moe, M., Kratter, K. M., & Badenes, C. 2019, ApJ, 875, 61
Rosen, A. L., Offner, S. S. R., Sadavoy, S. I., et al. 2020, SSRv., 216, 62
Rosen, A. L. 2022, arXiv:2204.09700
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, *Science*, 337, 444

Shimonishi, T., Onaka, T., Kawamura, A., et al. 2016, ApJ, 827, 72
Tanaka, K. E. I. & Omukai, K. 2014, MNRAS, 439
Tanaka, K. E. I., Tan, J. C., & Zhang, Y. 2017, ApJ
Tanaka, K. E. I., Tan, J. C., Zhang, Y., et al. 2018, ApJ, 861, 68