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# Gas and star formation in M33: an artistic pathway

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**Abstract** M33 is the closest blue, star forming, flocculent spiral galaxy for which it has been possible to combine an overwhelming quantity of multiwavelength high resolution data to shed light on its assembly and star formation across cosmic time. I will summarize some of the key ingredients related to the formation and evolution of this galaxy, such as its dark matter, the baryonic distribution and the metallicity gradients. M33 is a pure disk galaxy with a lower baryonic fraction than M31, of order 0.02, and a dark matter profile typical of structure growth in $\Lambda$CDM cosmology. Disk dynamics and the growth of perturbations can be visualized in a detailed 2-D map. The consequent star forming sites across the disk, analyzed using mid-infrared observations, points out young stellar clusters spanning 4 order of magnitude in luminosity. This database has allowed to study the IMF sampling at high mass end and the concept of a cluster birthline. Stars and gas, present beyond 2-optical radii points out to the occurrence of possible cosmic gas infall fueling star formation. Bruce Elmegreen outstanding contribution to science becomes evident in the analysis of M33, here underlined also through an artistic pathway.

## 1 Prologue

In the last few years the interest towards the possibility that cosmic gas accretion regulates star formation in galaxies has grown, a drawback for closed box models in galaxy evolution. Science evolves as human relations do too, you get to know new people at unpredictable moments. I have met Bruce 10 years ago at the IMF@50 meeting in Spineto. Being the organizer of that meeting I have not had the chance to really know Bruce until, as a result of a question to him a couple of years later, we worked together on M33 stellar clusters (Corbelli et al. 2009). When the referee report arrived, in the fall 2008, I was in the US, visiting Ed Salpeter during his last

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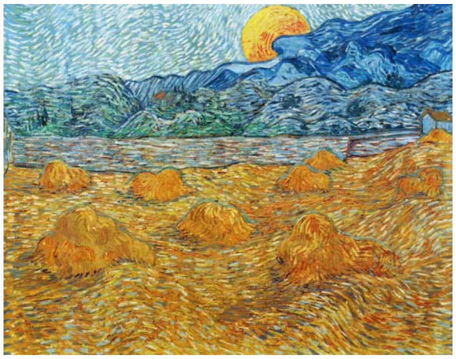
illness. Bruce kindly offered me to meet to work on the report in a museum of my choice in Manhattan on my way back home. Since I love modern art, I had no doubt: the only museum I would have loved to see again was the Museum of Modern Art. At MOMA there was an astonishing unexpected surprise, a temporary exhibition on *van Gogh and the Colors of the Night*. This stimulated my curiosity in investigating deeply later on the relation between van Gogh, one of my favorite painters, and astronomy. My contribution to these proceedings starts with the attempt to relate the astronomical knowledge and imagination present in van Gogh paintings to recurrent themes in Bruce's papers, often used in the analysis of M33.

During a working period in a bookshop and his long visit to Paris, van Gogh become aware of the emergence of a new science, astrophysics. The expanding knowledge of what stars are made of, the view of a non static cosmos spread across Europe thanks to books of popular science such as those by C. Flammarion. Van Gogh is aware of the colors and spectral classification of stars, of the sun as a star with a hot corona, of the spiral structure of some of the nebulae, and of the attempt to understand the shape and extent of the Milky Way. That is what made him conclude that ”putting little white dots on the blue-black is not enough to paint a starry sky”. While in Provence he makes the transition from prospective skies to ones full of colors, movement and imagination. For example in the celebrated painting Starry Night one sees stars of different colors and sizes, stars with an interior and an atmosphere, the endless flowing spiral which, because of its extent, recalls the Milky Way, but which might as well be the faint M33 nebula. M33 is in fact the closest known nebulae to the Aries constellation, clearly painted by van Gogh because present in the sky that night, just before the dawn of June 19 1889. The Starry Night has real and conceptual elements, also linked to religion. Van Gogh clearly wants to go beyond the current knowledge of astrophysics because painters, as he use to write, should uses the power of their imagination to go deeper, beyond what the eyes can see.

We know today of the importance of many conceptual elements present in van Gogh paintings and well understood one century later in astrophysics and underlined in Bruce's contributions to science. I will highlight here two of them: the understanding and measure of the stellar Initial Mass Function, from the solar neighborhood to primordial galaxies, and the relevance of spiral density waves and of turbulence in the gas-to-star conversion. Turbulence is what keeps galaxies alive slowing down the star formation efficiency, and turbulence is also what makes the landscape and people alive in the late artistic work of van Gogh. You can find it in day and night skies, in the backgrounds of portraits as well as in Bruce's papers. In many studies of M33 carried out with my collaborators I have often found Bruce's work very helpful and often M33 has confirmed his theoretical predictions. There is, however, an exception, and that concerns dark matter. Similarly, there is also one element in van Gogh paintings which seems uncorrelated to Bruce work or interests: the moon. The gibbous or waxing moon is a recurrent element in van Gogh work. A full moon is present in the artistic work Landscape with Wheat Sheaves and Rising Moon made in July 1889. Here, part of the moon has a reddish color. And what I have discovered by checking the lunar eclipse calendar around the time van Gogh was painting the raising moon with a red shadow, is that a moon eclipse was visible

**Fig. 1** The Starry Night painted by V. van Gogh in June 1889 with many astrophysical concepts emerging at the end of the XIX century: stars of different colors and sizes with a structure, the moon and Venus (outlined in red), the Aries constellation (in green), and a large flowing spiral nebula.

**Fig. 2** Landscape with Wheat Sheaves and Rising Moon by V. van Gogh. The moon has a reddish color close to the mountain since the painter wants to emphasize the moon eclipse which took place in southern France in July 1989.



in southern France at that time ! This confirms van Gogh love and interest for astronomy. Despite I know very little of Bruce (and about his interests on moon science) I had the chance to appreciate his care for people which makes him a great scientist to have around at any meeting.

## 2 Young Stellar Clusters and the IMF

Many years have past since the first description of M33 spiral arms appeared in a scientific journal, as ”swarms of meteorites” in the sky. We know today that spiral arms host the brightest HII regions of M33 because here giant molecular clouds grow by disk gravitational instabilities or collisions and coalescence. However it is become more and more evident that star formation in M33 is present throughout the whole disk in small units (Verley et al. 2009, Corbelli et al. 2011), and there is also evidence of occasional events in the extended warped gaseous disk (Sharma et al. 2011, Grossi et al. 2011). Thanks to Spitzer satellite 24 $\mu$m data it has been possible to select Young Stellar Cluster candidates spanning 4 orders of magnitude, in bolometric luminosity, down to $10^{37}$ erg $s^{-1}$ as faint as embedded B2-type stars. YSC mid-infrared photometry needs to be complement with UV data from the GALEX satellite to estimate luminosities because M33 has a low dust content (Verley et al. 2009, Grossi et al. 2010). Moreover, AGB stars contribute to the faint 24 $\mu$m source population in M33 and need to be identified. The YSC mass and size are correlated with a log-log slope of 2.09  0.01, similar to that measured for giant molecular clouds in M 33 and the Milky Way, which represent the protocluster environment. Faint clusters make up a non negligible fraction of the total star formation rate of M33 but their masses and ages have large uncertainties due to the lower probability of finding hot stars compared to brighter counterparts. When the IMF is not fully populated up to its high mass end, stochastic sampling of the IMF can take place and hot stars are born randomly in some clusters (e.g. Corbelli et al. 2009). Stochasticity allows for example a $5 \times 10^{39}$ erg $s^{-1}$ luminous cluster to be made by a single “outliers”, a 100 $M_\odot$ star, or by a more massive ensemble of small mass stars distributed according to a fully populated IMF up to about 30 $M_\odot$. If instead clusters are populated according to a truncated IMF, whose maximum stellar mass depends on cluster mass (Weidner & Kroupa 2006), no high mass stars can ever be formed in intermediate mass clusters. Large cluster samples can indeed be used to analyze the IMF at its high mass end using two integrated observables: the cluster bolometric and H$\alpha$ luminosity. To test IMF sampling in YSC Corbelli et al. (2009) have introduced the concept of cluster birthline. The cluster birthline is the place in the log $L_{bol}$ – log $L_{bol}/L_{H\alpha}$ plane where newborn young stellar clusters lie. If the stellar cluster is massive enough that the IMF is fully populated up to its high mass end, the ratio between the bolometric and H$\alpha$ luminosity is constant and it does not depend on the cluster mass. For stars less massive than 20 $M_\odot$ the H$\alpha$ luminosity drops with stellar mass much more quickly than the bolometric luminosity does. This implies that when the newly born cluster is small and very massive stars are lacking the birthline turns up towards higher values of log $L_{bol}/L_{H\alpha}$ and its exact shape depends on whether the IMF is stochastically sampled or truncated according to the cluster mass. An important property of the cluster birthline is that aging moves the clusters above it. This is because the death of massive stars makes the cluster H$\alpha$ luminosity fade away more rapidly than the bolometric luminosity does. For a given IMF the cluster birthline is a theoretical lower boundary for the $L_{bol}/L_{H\alpha}$ ratio. In fact possible leakage or dust absorption of ionizing photons in the HII region increases the

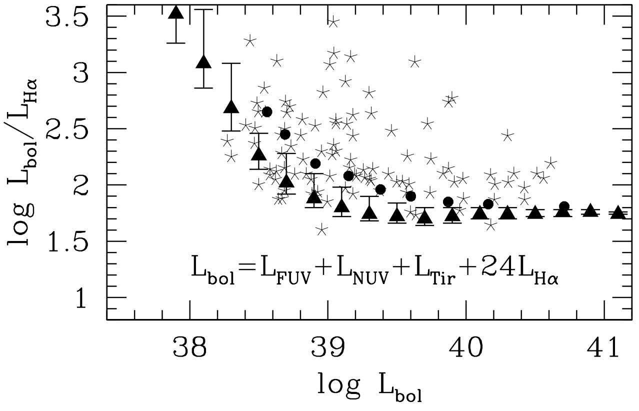


**Fig. 3** The cluster birthline. Filled triangles show the resulting birthline for clusters with a stochastically sampled IMF while the filled dots are for clusters populated according to a truncated IMF with a maximum stellar mass. Clusters are born along the birthline and aging moves them upward. No clusters can be found below the birthline. Star symbols show the locations of a MIR selected sample of YSC in M33 in better agreement with a stochastic universal IMF

value of the observed $L_{bol}/L_{H\alpha}$ ratio. In Figure 3 we compare the observed values of $L_{bol}/L_{H\alpha}$ ratio for an infrared selected sample of stellar clusters in M33 with the cluster birthline relative to the maximum mass case and to the case of a universal stochastically sampled IMF. As discussed by Corbelli et al. (2009) a stochastically sampled universal IMF is in better agreement with the data. Since 2009 there has been other evidence in favor of a stochastically sampled IMF (e.g. Corbelli et al. 2011 for MIR sources embedded in CO clouds which lie along the birthline).

## 3 Disk dynamics and star formation: from the center to the galaxy outskirts

Moving up to larger scales one interesting issue is to look at the disk dynamics and instabilities which trigger star formation. M33 is a smaller, more quiescent and younger galaxy than M31; it is bulgeless and hosts a higher SFR per unit area and a more extended gaseous disk than the brighter Local Group spirals. Using extinction corrected UV and H$\alpha$ maps we estimate a global SF rate in M 33 over the last 100 Myr to be 0.45± 0.10 M$_\odot$/yr (Verley et al. 2009). The SF rate declines radially with a scale length of about 2 kpc, The development of disk instabilities, with the consequent formation of new stars, has been widely studied by Bruce using a two component model (e.g. Elmegreen 1991, 1995, 2011, Hunter et al. 1998). Following Elmegreen's work and using azimuthal averages of the gas and stellar surface density (this last one from the dynamical analysis of the rotation curve) Corbelli (2003) has shown that Toomre and shear rate criteria are effective in explaining the drop in the SFR beyond 7 kpc, as indicated by the H$\alpha$ surface brightness. But the proximity of M33 allows to go one step further. The number of surveys today's available and the high resolution power for Local Group galaxies has stimulated the current effort of one of my collaborator at Arcetri, C. Giovanardi, who has been looking at resonances and producing a full map of the instabilities in the M33 disk. This has been possible thanks to the stellar surface density map of the bright optical disk by synthesis models, to the new rotation curve, and to the dispersion map resulting from the 21-cm VLA database (Corbelli et al. 2014). A first analysis of the instability maps of M33 suggest that the shear rate criteria is more effective in the innermost regions and along the two bright spiral arms while in the rest of the optical disk unstable filaments according to the Toomre criterion with the use of the epicyclic frequency are in place. We show in Figure 4 one example of the M33 disk instability map.

A weak small bar might be in the process of formation in the center but no clear evidence of a bulge has been found (Corbelli & Walterbos 2007). Further out several flocculent spiral arms form (Elmegreen 2003). Following the Tremaine & Weinberg (1984) method C. Giovanardi has determined the pattern speed to be about

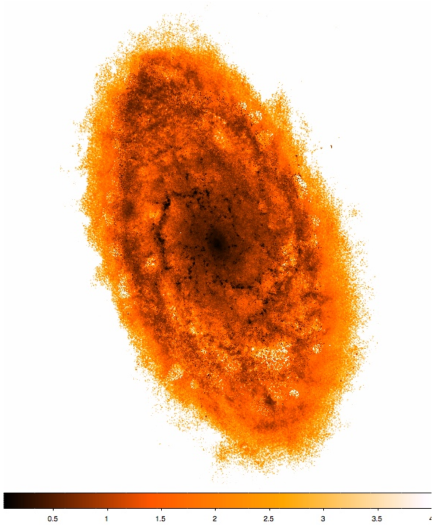


**Fig. 4** A Q-map of the optical disk of M33. Darker regions are prone to instabilities and fragmentation. *Courtesy of C. Giovanardi).*

17 km $s^{-1}$ $kpc^{-1}$ with no inner resonance, an outer resonance in the outer disk at about 12 kpc and corotation at 5.7 kpc. The stellar mass surface density map made via synthesis models using optical colors, highlights a steeper disk mass scalelength in the innermost kpc where the mass-to-light ratio is also higher. The mass-to-light ratio map is shown in Figure 5 where local variations can be seen, such as the contrast between arm and interarm regions.

The outer disk of M33 is not a pure gaseous disk but host stars as well. There is not only evidence of an extended star-formation episode 2.5 Gyrs ago but also of more recent ones: deep optical surveys have in fact revealed stars of about 200 Myrs of age (Grossi et al. 2011) and MIR surveys have found evidence of possible star forming sites as young as 10 Myrs (Sharma et al. 2011). It is likely that in the outer disk star formation is not persistent but major events occur in bursts triggered either by interactions or by gas accreting, as explained better in the next Section.

## 4 The dark halo and the evolution of M33

The evolutionary history of M33 can be understood by selecting a chemical evolution model which reproduces the observed distribution of gas, star formation, metals etc. but also by pinning down the main characteristics of its dark matter halo. The halo is important not only because it provides a link to the cosmological model and to the galaxy formation process but also for understanding the past and future tidal interactions with other group members. It is still an open question whether galaxies like M33 will be refilled by accreting gas and keep on forming stars or else will be starving after a close encounter with a massive group member. The dynamical analysis of the rotation curve of M33, recently traced by Corbelli et al. (2014), has shown unambiguously that a dark matter halo with a Navarro-Frenk-White (Navarro et al. 1997) density profile, mass and concentration as predicted by hierarchical clustering

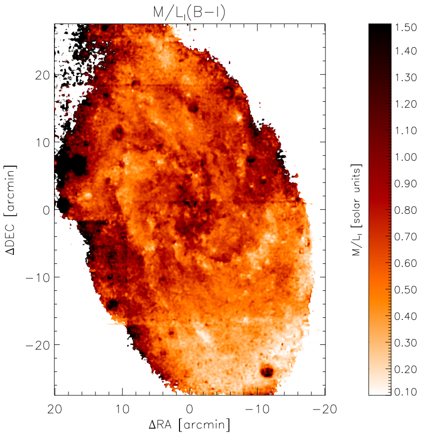
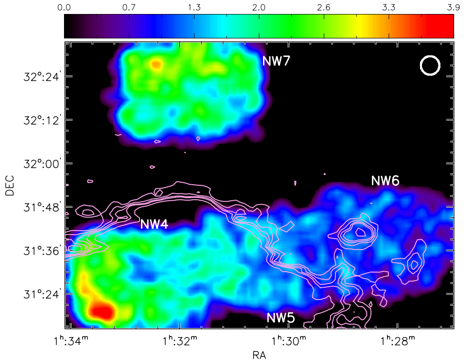


**Fig. 5** The mass-to-light ratio map in the star forming disk of M33 from accurate stellar mass synthesis models of the light distribution observed by in several bands by Massey et al. (2006).

**Fig. 6** The distribution of stars in the northern part of the outer disk. As discussed by Grossi et al. (2011) in the outer disk there is evidence of an intermediate age stellar population with a scalelength similar to that of the local atomic gas counterpart.



and structure formation in a $\Lambda$CDM cosmology (Maccio' et al. 2008), is in place. Dark matter is relevant at all radii in shaping the rotation curve and the most likely dark halo has a concentration C$\simeq$10 and a total mass of 4.3($\pm$ 1.0) $10^{11}$ $M_\odot$. This, given the stellar and gaseous mass maps, implies a baryonic fraction of order 0.02 and the evolutional history of this galaxy should account for loss of a large fraction of its original baryonic content. The low baryonic fraction of M33 is puzzling in the frame of the most recent picture that emerged from the proper motion measurements of M31 and M33 and of the satellite plane found around M31. These findings imply that M33 is now approaching M31 and has not been already disrupted by M31 tidal forces (van der Marel et al. 2012, Shaya and Tully 2013). Hence the low baryonic fraction should results from internal removal mechanism such as outflows or by some mechanism that prevented the collapse of a large gas fraction into the disk. The recent estimate of the average galaxy baryonic content as a function of halo mass, as from the halo to stellar luminosity function matching technique, underline the fact that galaxies with the same halo mass as M33 do indeed have a similar low baryonic content (Moster et al. 2010,2013). The halo mass we find for M33 is sufficiently high to prevent a softening of the dark matter cusp due to past outflows from the nuclear region of M33 (di Cintio et al. 2014).

For the halo mass of M33 it is still possible to have accretion from cosmic filaments at z=0 to fuel star formation. Grossi et al. (2008) have found HI clouds associated with the circumgalactic medium of M33 which follow the rotational pattern of the galaxy. Given the low observed HI column densities, these clouds are

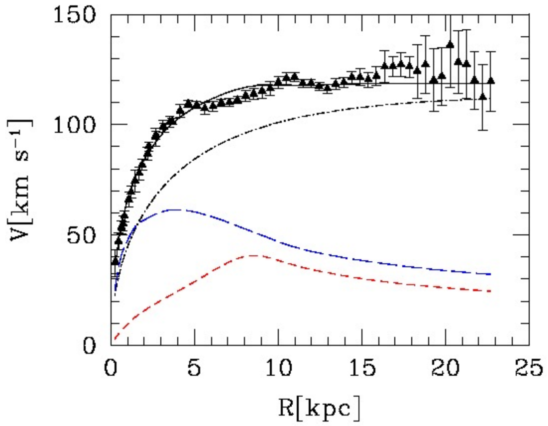


**Fig. 7** The rotation curve of M33 from CO (FCRAO) and HI (VLA) data with the best fitting $\Lambda$CDM dark halo model (dot-dashed line), the stellar and gas (long and short dashed lines respectively) contributions to it. The stellar mass map with its error bars has been used to compute the stellar contribution to the rotation curve and the molecular gas surface density has been added to the atomic gas distribution (Corbelli et al. 2014).

likely to be highly ionized by the extragalactic ultraviolet radiation and the total gas mass associated with them is $> 5x10^7$ $M_\odot$. If the gas is steadily falling towards the M33 disc, (there signs of non circular motion in the outer disk with amplitude of 10 km s$^{-1}$) it can provide the fuel needed to sustain the current star formation rate. The unlikely occurrence of a closer encounter between M33 and M31 in the past does not support their tidal origin, and the absence of stellar structures within the clouds (Grossi et al. 2011) supports their association with the neutral parts of cosmic filaments which cool and recombine after entering the potential well of M33. The gas accreting into the outer disk has its angular momentum aligned with the cosmic filaments, tilted with respect to the inner disk which formed early on. The chemical evolution model of M33, which reproduces the metallicity gradient and its time evolution, the baryonic distribution and the star formation rate in this galaxy (Magrini et al. 2010) requires a slow gas accretion rate through cosmic time.

## References

1. Corbelli, E. 2003, MNRAS, 342, 199
2. Corbelli, E. and Walterbos, R. A. M. 2007, ApJ, 669, 315
3. Corbelli, E., Verley , S., Elmegreen B. G. and Giovanardi, C. 2009, A&A, 495, 479

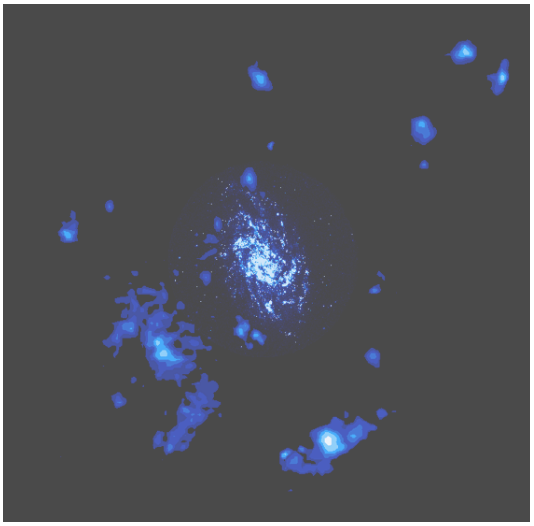


**Fig. 8** The HI clouds in the circumgalactic medium of M33 observed with the Arecibo telescope by Grossi et al. (2008) overplotted on the GALEX image of the star forming disk of the galaxy.

4. Corbelli, E., Giovanardi, C., Palla, F., and Verley, S. 2011, A&A, 528, 116
5. Corbelli, E., Thilker, D., Giovanardi, C., Zibetti, S. and Salucci, P. 2014, A&A, submitted
6. Di Cintio , A., Brook , C. B., Macciò , A. V. Stinson, G. S., Knebe, A., Dutton , A. A., and Wadsley , J. 2014, MNRAS, 437, 415
7. Elmegreen , B. G., Leitner , S. N., Elmegreen , D. M. and Cuillandre , J.-C. 2003, ApJ, 593, 333
8. Elmegreen, B. G. 1995, MNRAS, .275, 944
9. Elmegreen, B. G. 2011, ApJ, 737, 10
10. Elmegreen , B. G. 1991, ApJ, 378, 139
11. Grossi, M., Giovanardi, C., Corbelli, E., Giovanelli, R., Haynes , M. P., Martin, A. M., Saintonge, A. and Dowell, J. D. 2008, A&A, 487, 161
12. Grossi, M., Corbelli, E., Giovanardi, C. and Magrini, L. 2010, A&A, 521, 41
13. Grossi, M., Hwang, N., Corbelli, E., Giovanardi, C., Okamoto, S., and Arimoto , N. 2011, A&A, 533, 91
14. Hunter, D. A. and Elmegreen , B. G. and Baker , A. L. ,1998, ApJ, 493, 595
15. Macciò , A. V. and Dutton , A. A. and van den Bosch , F. C. 2008, MNRAS, 391,1940
16. Magrini, L. and Stanghellini , L. and Corbelli , E. and Galli , D. and Villaver , E. , 2010, A&A, 512, 63
17. Massey , P. and Olsen , K. A. G. and Hodge , P. W. and Strong , S. B. and Jacoby , G. H. and Schlingman , W. and Smith , R. C., 2006, AJ, 131, 2478
18. Moster, B. P. , Somerville , R. S., Maulbetsch , C., van den Bosch , F. C., Macciò , A. V., Naab, T. and Oser , L. 2010, ApJ, 710, 903
19. Moster, B. P., Naab, T., and White, S. D. M. 2013, MNRAS, 428, 3121
20. Navarro, J. F., Frenk , C. S., and White , S. D. M. 1997, ApJ, 490, 493
21. Sharma, S., Corbelli, E., Giovanardi, C., Hunt, L. K. and Palla, F. 2011, A&A, 534, 96
22. Shaya , E. J. and Tully , R. B. 2013, MNRAS. 436, 2096
23. Tremaine , S. and Weinberg, M. D. ,1984, ApJ, 28, 5
24. Verley, S., Corbelli, E., Giovanardi, C. and Hunt L. K. 2009, A&A 493, 453
25. Weidner, C. and Kroupa , P. 2006, MNRAS, 365, 1333
26. van der Marel , R. P., Besla , G., Cox , T. J., Sohn , S. T., and Anderson, J. 2012, ApJ, 753, 9