WR 72: a born-again planetary nebula with hydrogen-poor knots

V. V. Gvaramadze,1,2* A. Y. Kniazev,3,4,1 G. Gräfener5 and N. Langer5

1Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetsky Pr. 13, Moscow 119234, Russia
2Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia
3South African Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa
4Southern African Large Telescope Foundation, PO Box 9, 7935 Observatory, Cape Town, South Africa
5Argelander-Institut für Astronomie, Auf dem Hügel 71, 53121 Bonn, Germany

Accepted 2019 December 21. Received 2019 December 20; in original form 2019 November 26.

ABSTRACT
We report the discovery of a handful of optical hydrogen-poor knots in the central part of an extended infrared nebula centred on the [WO1] star WR 72, obtained by spectroscopic and imaging observations with the Southern African Large Telescope (SALT). Wide-field Infrared Survey Explorer (WISE) images of the nebula show that it is composed of an extended almost circular halo (of ≈ 6 arcmin or ≈ 2.4 pc in diameter) and an elongated and apparently bipolar inner shell (of a factor of six smaller size), within which the knots are concentrated. Our findings indicate that WR 72 is a new member of the rare group of hydrogen-poor planetary nebulae, which may be explained through a very late thermal pulse of a post-AGB star, or by a merger of two white dwarfs.

Key words: stars: AGB and post-AGB – circumstellar matter – stars: individual: WR 72 – stars: winds, outflows

1 INTRODUCTION
Among planetary nebulae (PNe) there is a rare group of objects showing hydrogen-poor (H-poor) material in the central region of older and larger hydrogen-rich nebula (Jacoby 1979; Hazard et al. 1980; Jacoby & Ford 1983; see also Zijlstra 2002 for a review). In the two best-studied members of this group, A30 (PN A66 30) and A78 (PN A66 78), the H-poor material appears as a fan of knots with cometary tails, stretched radially from the central star (e.g. Borkowski et al. 1993, 1995; Fang et al. 2014). The 3D distribution of the knots suggests the existence of an equatorial disc-like structure and polar outflows with individual knots moving outwards with velocities of ~ 100 km s−1 in the equatorial ring and at a factor of several higher velocities in the polar directions (e.g. Borkowski et al. 1995; Chu et al. 1997; Fang et al. 2014).

The origin of the knots could be understood as the result of instabilities developed during the interaction between the current fast wind and ionizing emission of the central star of PN (CSPN) with the slow dense H-poor material lost by the star shortly before (e.g. Fang et al. 2014). Some of the knots have cold, neutral cores, as evidenced by the detection of molecular emission at (sub)millimeter wavelengths (Tafoya et al. 2017). The optical emission from these knots comes from the ionized skin around the neutral core. The material photoevaporated and ablated from the knots could be hot and dense enough to produce observable X-ray emission (Chu et al. 1997; Guerrero et al. 2012; Toalá et al. 2015).

It is believed that the origin of the H-poor material is due to very late thermal pulse (VLTP; Fujimoto 1977; Schönberner 1979; Iben et al. 1983), leading to the (almost) total burning of the remaining hydrogen shell in the star (e.g. Herwig et al. 1999). Under the influence of the VLTP, the CSPN expands and cools, and finds itself again at the asymptotic giant branch (AGB). During this “born-again” episode the CSPN develops a slow H-poor wind, which is fragmented in knots when the star leaves the AGB for the second time and again starts to produce fast wind.

On the other hand, the axially symmetric distribution of the knots suggests that the origin of the H-poor PNe could be somehow related to the binarity of their central stars or to a combination of the binary evolution and the VLTP in one of the binary components (e.g. Harrington 1996; Wesson et al. 2008; de Marco 2008; Lau et al. 2011; Gvaramadze et al. 2019b). Revealing new members of the group of H-poor PNe is therefore of high importance for understanding...
their nature and for the theory of low-mass star evolution in general. In this paper, we show that WR 72 is a new member of this rare group.

2 WR 72 AND ITS CIRUMSTELLAR NEBULA

WR 72 (or Sand 3; Sanduleak 1971) is a hydrogen-deficient, ultrahigh-excitation star exhibiting a Wolf-Rayet-type spectrum (Barlow, Blades & Hummer 1980). Originally, it was listed in the Sixth Catalogue of Galactic Wolf-Rayet stars (van der Hucht et al. 1981) as a peculiar WC4 star, but was omitted from the later editions of the catalogue after it was reclassified as a CSPN by Barlow & Hummer (1982). The main reasons for this reclassification are the high-latitude ($b \approx 12^\circ$) location of the star and the presence of the $N\,\lambda 1238 \text{ Å}$ line in its UV spectrum, which is not expected in massive stars as they completely destroy nitrogen in the early stages of helium burning. According to the classification scheme of Crowther et al. (1998), WR 72 is a [WO1] star. In the SIMBAD data base, WR 72 is indicated as a PN.

Since no PN associated with WR 72 was found at the time, Barlow & Hummer (1982) suggested that it has already dispersed in the interstellar medium and is no longer detectable. Later on, van der Hucht et al. (1985) detected an unresolved infrared (IR) source centred on WR 72 using 50 and 100 $\mu$m data from the Infrared Astronomical Satellite (IRAS) Chopped Photometric Channel instrument, and presented the IRAS flux densities for this source at 12, 25, 60 and 100 $\mu$m (taken from the IRAS Point Source Catalogue). Using these flux densities, they constructed spectral energy distribution of the IR source and treated it as a dust shell with a temperature within the range of temperatures found in PNe. The subsequent search for an optical nebula around WR 72 using a narrowband H$\alpha$ filter gave a negative result (Marston et al. 1994). Feibelman (1996) found evidence of nebular emission lines (produced by triply or higher ionized species) in the International Ultraviolet Explorer (IUE) spectrum of WR 72, but regarded this star as a “central star without planetary nebula” because no classical PN has ever been detected. The nebula also was not detected in the Hubble Space Telescope (HST) UV spectrum of WR 72 (Keller et al. 2014), which again was considered as a prove that it has already dispersed.

Still, the nebula around WR 72 exists! We found it as a by-product of our search for massive evolved stars through the detection of their circumstellar nebulae (Gvaramadze

---

1 http://simbad.u-strasbg.fr/simbad/

2 Note that the IRAS Small Scale Structure Catalog (Helou & Walker 1988) gives for this source an angular diameter of 1.3 arcmin at 25 $\mu$m.
et al. 2010, 2012). The nebula was detected in the data of the all sky survey carried out with the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), which provides images at four wavelengths: 22, 12, 4.6 and 3.4 μm, with angular resolution of 12.0, 6.5, 6.4 and 6.1 arcsec, respectively, and it is clearly seen at all four WISE wavebands. The literature search revealed that the nebula was first detected by Griffith et al. (2015), who used the WISE data to search for objects with extreme mid-IR colours, which might be associated with extraterrestrial civilizations with large energy supplies. Since the SIMBAD data base indicates a PN at the position of the nebula it was graded by Griffith et al. (2015) as a source whose nature is well understood, and correspondingly no images of the nebula were presented.

In Fig. 1 we show for the first time the WISE images of the nebula around WR 72. At 22 μm it appears as an almost circular (but slightly elongated in the north-south direction) diffuse halo (of angular diameter of ≈ 6 arcmin) surrounding a core of bright emission centred around WR 72. Interestingly, the peak of this emission is shifted to the southwest of WR 72 (see Fig. 2). At 12 μm the halo is not visible, while the central core is resolved in an asymmetric structure of angular size of ≈ 1 arcmin surrounded by diffuse emission of the same size as the bright core in the 22 μm image. Within this diffuse emission one can distinguish several radial spokes stretched to the northeast and northwest. At shorter wavelengths (4.6 and 3.4 μm) the nebula appears as an elongated (apparently bipolar) shell of angular size of ≈ 1 arcmin. The Gaia second data release (DR2; Gaia Collaboration et al. 2018) parallax of 0.705 ± 0.039 mas places WR 72 at the distance of ≈ 1.42 ± 0.08 kpc. At this distance, the linear sizes of the halo and the central shell are, respectively, ≈ 2.4 and 0.4 pc.

We did not find an optical counterpart to the IR halo in the available optical sky surveys, but noticed a knot of diffuse emission at ≈ 10 arcsec to the southwest from WR 72 in the blue-band image (see Fig. 2) from the Digitized Sky Survey II (DSS-II; McLean et al. 2000). The non-stellar origin of this emission is more obvious in the blue-band image (see Fig. 2) from the SuperCOSMOS Sky Survey (SSS; Hambly et al. 2001). The gleam of the knot is also visible in the SSS red-band image (see Fig. 2) and can be discerned in the DSS-II red-band image (not show in Fig. 2). Comparison of the IR and optical images shows that the knot coincides with the peak of the 22 μm emission (see Fig. 2).

The SIMBAD database lists the IRAS source 16032–3537 at ≈ 9 arcsec to the southwest from WR 72 and notes that “IRAS16032–3537 is not WR 72”. The detection of the IR nebula around WR 72, whose brightness peaks at the position of the IRAS source, implies that this source is in fact associated with WR 72.

### 3 SALT OBSERVATIONS

To reveal the nature of the optical knot, we observed it with the South African Large Telescope (SALT; Buckley et al. 2006; ODonoghue et al. 2006). First, we took its spectrum using the Robert Stobie Spectrograph (RSS; Burg et al. 2003; Kobulnicky et al. 2003) in the long-slit spectroscopy mode on 2019 July 16. A 8 arcmin×1.5 arcsec slit was placed on the knot at the position angle PA=45° (see Fig. 5). Two 1000s exposures were obtained using the PG900 grating. This spectral setup covers a wavelength range of 3750 – 6850 Å with a spectral resolution FWHM of ≈ 0.3 Å. The seeing during these observations was ≈ 2.1 arcsec. A spectrum of an Ar comparison arc was obtained immediately after that to calibrate the wavelength scale. For the relative flux calibration a spectrophotometric standard star EG 21 (Baldwin & Stone 1984) was observed with the same spectral set-ups during nearest twilights as a part of the SALT calibration plan. The absolute flux calibration is not possible with SALT because the unfilled entrance pupil of the telescope moves during the observations.

Then, we observed WR 72 using the RSS imaging mode on 2019 August 6. A 900s exposure was taken with the filter P105060 (λ=5071.5 Å, FWHM=110.5 Å) to cover the [OIII] λ5007 Å emission line. Also, a 900s exposure was taken with the filter P105145 (λ=5152.1 Å, FWHM=109.2 Å) to obtain an image free from emission lines, to remove stellar confusion. The seeing in these observations was ≈ 1.6 arcsec. Both images were binned by a factor of 4 to get the final spatial sampling of 0.5 arcsec pixel$^{-1}$.

The primary reduction of the RSS data was done with the SALT science pipeline (Crawford et al. 2010). The subsequent long-slit data reduction was carried out in the way described in Kniazev et al. (2008).

### 4 SPECTRUM OF THE OPTICAL KNOT

The 1D spectrum of the optical knot is presented in Fig. 2. It was extracted by summing up, without any weighting, all rows in the brightest part of the knot (i.e. in the angular distance interval from −7 arcsec to −12.5 arcsec; see Fig. 4). The spectrum is dominated by the strong [OIII] λλ4959, 5007 Å doublet. The next strongest emissions are due to the [NeIII] λλ3869 Å, He II λλ4686 Å and [NII] λλ6584 Å lines. The emission line at the position of the He II λλ6586 Å + Hα blend is very weak.

The detected lines are listed in Table 1 along with their observed intensities (normalized to He II λλ4686 Å) and the reddening-corrected line intensity ratios (derived for E(B − V) = 0.4 mag; Keller et al. 2014). The electron temperature diagnostic line [OIII] λ4363 Å is not visible in the spectrum. For this line we provide the upper limit assuming that its intensity is equal to the 1σ noise level.

The very low intensity of the He II+Hα blend suggests that the knot is H-poor. To constrain its H/He abundance

| λ$_0$(˚) | $F(\lambda)/F$(He II 4686) | $I(\lambda)/I$(He II 4686) |
|---------|--------------------------|--------------------------|
| 3868    | 2.33±0.20                | 3.14±0.28                |
| 4363    | <0.14                    | <0.16                    |
| 4686    | 1.00±0.09                | 1.00±0.09                |
| 4715    | 0.50±0.07                | 0.49±0.07                |
| 4725    | 0.61±0.09                | 0.60±0.09                |
| 4959    | 7.00±0.47                | 6.41±0.43                |
| 5007    | 21.02±1.42               | 18.94±1.29               |
| 6548    | 0.22±0.05                | 0.13±0.03                |
| 6560    | 0.21±0.05                | 0.13±0.03                |
| 6584    | 0.94±0.08                | 0.57±0.06                |
ratio, we compare the observed H/He line ratio with theoretical estimates. The observed He emission originates in a region where helium is fully ionized to He++. In the following we obtain an upper limit for the H abundance by estimating the He and H emission originating from this region alone.

We compute the strengths of the components of the H+He blend relative to He 4686 using theoretical line emissivities for hydrogenic ions from Martin (1988), and the scaling relation between line emissivities of hydrogenic ions with core charge Z at electron temperature T:

\[ j_{n,n'}(Z,T) = Z^3 j_{n,n'}(1,T/Z^2) \].

Using the upper limit on the [OIII] λ4363 Å line intensity (see Table 1) and \( E(B-V) = 0.4 \) mag, one finds \( T \lesssim 10500 \) K. Assuming two times lower line intensity gives \( T \lesssim 8900 \) K. We further adopt \( T = 10000 \) K.

Because of the small spatial extent of the He-emitting knot it is likely that radiation emitted through recombination into the ground state escapes without being re-absorbed, i.e. case A recombination can be adopted. For the He/He 4686 line ratio we obtain from Martin (1988) that \( j_{\text{HeII} 4650}/j_{\text{HeII} 4686} = 0.136 \) for case A recombination. For case B we obtain a very similar value. This means that, within the given error margins, the observed (H+He)/He 4686 line ratio of 0.14 ± 0.03 (see Table 1) can be explained by the He emission alone.

For the ratio of H/He 4686 in the He-emitting region we obtain from Eq. (1) that \( j_{\text{H}/j_{\text{HeII} 4686}} \approx [j_{3,2}(1,T)/8j_{4,3}(1,T/4)](n_p/n_{He^+}) \). Assuming that the He-emitting zone is fully ionized, we obtain

\[ j_{\text{H}}/j_{\text{HeII} 4686} = 0.162(n_p/n_{He}) \] (2)

for case A recombination, and 0.232\((n_p/n_{He})\) for case B. Case A thus provides a safe lower limit for the H abundance.

Based on our previous estimate for the He emission, the residual contribution of hydrogen to the H emission is \( j_{\text{H}}/j_{\text{HeII} 4686} < 0.034 \). Using Eq. (2), this translates into an upper limit of \( n_p/n_{He} < 0.2 \), meaning that the knot is (almost) free of hydrogen.

5 MORE KNOTS AROUND WR 72

Figure 3 plots the [OIII] λ5007 Å line intensity and the heliocentric radial velocity, \( v_{hel} \), distributions along the slit. The radial velocity was not measured in the area between –6 arcsec and +6 arcsec because of the effect of WR 72. The intensity distribution peaks at the position of the already known knot to the southwest of WR 72 and shows three additional peaks of lower intensity, one on the same side from WR 72 (at \( \approx -22 \) arcsec), and two other on the opposite side (at \( \approx +12 \) arcsec and +22 arcsec). As we will see below, these peaks correspond to three knots of optical emission of low surface brightness, which were intersected by the slit by chance (see Fig. 5). Besides these peaks, we did not detect any signatures of nebular emission within the boundaries of the IR halo nor along the whole extent of the 8 arcmin long slit.
Figure 4. [O\textsc{iii}] λ5007 Å line intensity (upper panel) and the heliocentric radial velocity (bottom panel) profiles along the slit. NE-SW direction of the slit is shown. The solid vertical line corresponds to the position of WR 72, while the dashed vertical lines (at ±6 arcsec from the solid one) mark the area where the radial velocity was not measured because of the effect of WR 72.

Figure 4 also shows that $v_{\text{hel}}$ changes along the slit, suggesting that the [O\textsc{iii}]-emitting material is moving relative to WR 72. The almost circular shape of the IR halo around WR 72 indicates that the space velocity of the star is much lower than the expansion velocity of the halo, meaning that the ram pressure of the interstellar medium did not affect the expansion of the stellar wind. Adopting the typical expansion velocity of PNe of $20-30 \, \text{km s}^{-1}$ (Gesicki & Zijlstra 2000), this condition would imply that the systemic velocity of WR 72 is close to zero. In this case, the radial velocity of the [O\textsc{iii}]-emitting material with respect to the star is given by $v_r = v_{\text{hel}} + 22.5 \, \text{km s}^{-1}$. Using this relation and Fig. 4, we speculate that the knot located at +12 arcsec could be an obscured redshifted counterpart to the bright knot, just as it was suggested by Pollacco et al. (1992) for the H-poor ejecta in the centre of the PN A58 (V605 Aql).

The existence of other knots around WR 72 is clearly illustrated by Fig. 4 which shows the [O\textsc{iii}] λ5007 Å and continuum-subtracted images of a 1.5 arcmin × 1.5 arcmin field centred on WR 72. One can see that besides the bright knot to the southwest from WR 72 (now resolved into two bright blobs) there is a number of faint knots scattered around the star. Some of them are elongated in the radial direction like in the fan-like systems of H-poor knots in the central regions of A30 and A78. Although the chemical abundances in the newly detected knots have yet to be determined, they apparently are H-poor as well.

A comparison with the WISE 4.6 μm image shows that all knots are located within the inner shell of the IR nebula, and that most of them are enclosed within its southeast lobe (see Fig. 4. The linear radius of the shell of $\approx 0.2$ pc and the typical radial velocity of knots in the H-poor PNe of $\sim 100 \, \text{km s}^{-1}$ (e.g. Chu et al. 1997) imply the age of the shell of $\sim 1000$ yr. Thus, WR 72 is of comparable age with the H-poor PNe A30 and A78, and is at a more advanced evolutionary stage than A58, which went through the born-again event, respectively, 610–950, 605–1140 and $\sim 100$ yr ago (Seitter 1987; Fang et al. 2014).

6 DISCUSSION

The detection of the H-poor knots within the more extended circular nebula around WR 72 indicates that this star belongs to the rare group of H-poor PNe (only a few such objects are known to date). Using the typical expansion velocity of PNe of $20-30 \, \text{km s}^{-1}$ (Gesicki & Zijlstra 2000), one finds the kinematic age of the IR halo around WR 72 of 40 000–60 000 yr. This age and the large radius of the halo (≈ 1.2 pc) are typical of old PNe (e.g. Pierce et al. 2004), meaning that the lack of optical emission from the halo could simply be because its surface brightness has fallen below the detectability threshold (for comparison, the radii of the optically visible outer H-rich parts of A30, A58 and A78 are, respectively, ≈ 0.8, 0.4 and 0.5 pc).

The origin of H-poor material in PNe and their central stars is usually attributed to a VLTP, which occurs after the extinction of the hydrogen burning shell when the star has already entered the white dwarf cooling track. The VLTP leads to the mixing and (almost) complete burning of the remaining hydrogen in the star, and results in a helium and CO-rich surface composition, which can also be nitrogen-enriched (Werner & Herwig 2006, Löbling et al. 2019). The chemical composition of WR 72 has been determined by Koesterke & Hamann (1997) and Keller et al. (2014). Both works consistently find high abundances of carbon and oxygen. Additionally, Keller et al. (2014) derive a surface mass fraction of nitrogen of 7 per cent for WR 72, discrepant with a value of 0.5 per cent found by Koesterke & Hamann (1997). In either case, the surface abundances of WR 72 appear to be consistent with a VLTP evolution.

It is also interesting to use the new Gaia distance of WR 72 for constraining its bolometric luminosity. For this purpose, we rescale the results of Koesterke & Hamann (1997) and of Keller et al. (2014), who derived the distance to WR 72 after adopting the bolometric luminosity of this star. This exercise leads to a luminosity of WR 72 of 8300 and 22 000 $L_\odot$, respectively. While the larger of the two values is about two times higher than the luminosities of the known [WO]-type CSPNs (Gesicki et al. 2006), both are well in the range of luminosities predicted by post-AGB stellar models (Blöcker 1995; Miller Bertolami 2016). A high luminosity for WR 72 could mean that its mass is high compared

---

3 To derive this relation, we used the solar Galactocentric distance and the circular Galactic rotation velocity from Reid et al. (2009), and the solar peculiar motion from Schönrich, Binney & Dehnen (2010).
to other [WC]-CSPNe, or that the masses and luminosities of [WC]-CSPNe have been underestimated in previous works.

While the VLTP scenario is consistent with the properties of WR 72, stars with similar properties, with C and O rich surfaces, and with hydrogen-deficient circumstellar nebulae, may also arise from the merging of two white dwarfs (Longland et al. 2011; Jeffery, Karakas & Suio 2011; Schwab, Quataert & Kasen 2016; Schwab 2019). In view of the interpretation of the [WO]-type star IPHAS J005311.21+673002.1 as a white dwarf merger product (Gvaramadze et al. 2019a) and the potentially high mass of WR 72 (see above), it remains possible that also WR 72 is the result of a white dwarf merger.

Follow-up deeper and higher resolution spectroscopy and imaging of the knots around WR 72 are needed to determine their abundances and to check whether their spatial distribution and kinematics are axially symmetric. The detection of axial symmetry can be seen as an indication that WR 72 is a binary system. On the other hand, during the born-again event, the luminosity of the post-VLTP star could exceed the Eddington limit, and thus even slow stellar rotation may break the spherical symmetry of the H-poor ejecta (Langer 1997).

Finally, WR 72 might be a promising target for the Atacama Pathfinder Experiment (APEX) and the current X-ray observatories because the bright knot to the southwest of WR 72 might have a cool molecular core (like in A58; Tafoya et al. 2017), while the inter-knot material could be heated to X-ray temperatures by the current fast (2200 km s$^{-1}$; Keller et al. 2014) stellar wind (as takes place in A30 and A78; Chu et al. 1997; Guerrero et al. 2012; Toalá et al. 2015).

7 ACKNOWLEDGEMENTS

This work is based on observations obtained with the Southern African Large Telescope (SALT), program 2019-1-MLT-002. V.V.G. acknowledges support from the Russian Science Foundation under grant 19-12-00383. A.Y.K. acknowledges support from the National Research Foundation (NRF) of South Africa. G.G. acknowledges financial support from Deutsche Forschungsgemeinschaft (DFG) under grant GR 1717/5-1. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, the SIMBAD database and the VizieR catalogue access tool, both operated at CDS, Strasbourg, France, and data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

REFERENCES

Baldwin J. A., Stone R. P. S., 1984, MNRAS, 206, 241
Barlow M. J., Hummer D. G., 1982, in De Loore C. W. H., Willis A. J., eds, Proc. IAU Symp. 99, Wolf-Rayet Stars: Observations, Physics, Evolution. Reidel, Dordrecht, p. 387
Barlow M. J., Blades J. C., Hummer D. G., 1980, ApJ, 241, L27
Blöcker T., 1995, A&A, 299, 755
Borkowski K. J., Harrington J. P., Tsvetanov Z. I., 1995, ApJ, 449, L143
Borkowski K. J., Harrington J. P., Tsvetanov Z., Clegg R. E. S., 1993, ApJ, 415, L47
Buckley D. A. H., Swart G. P., Meiring J. G., 2006, SPIE, 6267, 32
Burgh E. B., Nordsieck K. H., Kobulnicky H. A., Williams T. B., O’Donoghue D., Smith M. P., Percival J. W., 2003, SPIE, 4841, 1463
Chu Y.-H., Chang T. H., Conway G. M., 1997, ApJ, 482, 891
Crawford S. M. et al., 2010, SPIE, 7737, 25
Crowther P. A., De Marco O., Barlow M. J., 1998, MNRAS, 296, 367
De Marco O., 2008, in Hydrogen-Deficient Stars, eds. A. Werner, & T. Rauch, ASP Conf. Ser., 391, 209
Fang X. et al., 2014, ApJ, 797, 100
