Astronomy Letters, 2016, Vol. 42, No. 2, p. 63–68. Translated from Pis'ma v Astronomicheskij Zhurnal.

Additional spectroscopic redshift measurements for galaxy clusters from the First Planck Catalogue

V.S. Vorobyev[1], R.A. Burenin[*1], I.F.Bikmaev[2,3], I.M.Khamitov[2,4], S.N. Dodonov[5], R.Ya. Zhuchkov[2,3], E.N. Irtuganov[2,3], A.V.Mescheryakov[1,2], S.S. Melynikov[2,3], A.N. Semena[1], A.Yu. Tkachenko[1], N. Aghanim[6], R. Sunyaev[1,7]

[1] *Space Research Institute of the Russian Academy of Sciences, Moscow, Russia*
[2] *Kazan Federal University, Kazan, Russia*
[3] *Academy of Sciences of The Republic of Tatarstan, Kazan, Russia*
[4] *Scientific and Technological Research Council of Turkey, Antalya, Turkey*
[5] *The Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhnij Arkhyz, Russia*
[6] *Institut dÁstrophysique Spatiale, Orsay, France*
[7] *Max Planck Institute for Astrophysics, Garching, Germany*

Received September 3, 2015

Abstract — We present the results of spectroscopic redshift measurements for the galaxy clusters from the first all-sky Planck catalogue of the Sunyaev-Zeldovich sources, that have been mostly identified by means of the optical observations performed previously by our team (Planck Collaboration, 2015a). The data on 13 galaxy clusters at redshifts from $z \approx 0.2$ to $z \approx 0.8$, including the improved identification and redshift measurement for the cluster PSZ1 G141.73+14.22 at $z = 0.828$, are provided. The measurements were done using the data from RussianTurkish 1.5-m telescope (RTT-150), 2.2-m Calar Alto Observatory telescope, and 6-m SAO RAS telescope (Bolshoy Teleskop Azimutalnyi, BTA).

Keywords: *galaxies, galaxy clusters.*

INTRODUCTION

A large number ($\sim 10^3$) of galaxy clusters are detected in the Planck all-sky survey (Planck Collaboration, 2014b, 2015b,d) via the Sunyaev-Zeldovich (SZ) effect (Sunyaev and Zeldovich, 1972). The sensitivity of the survey turns out to be distributed nearly more or less uniformly over the entire sky. Since the SZ signal amplitude depends mainly on the mass of clusters and not on their redshift, all the most massive (with masses $> 6 \cdot 10^{14} M_\odot$) galaxy clusters in the Universe are detected in the Planck survey. This sample of galaxy clusters is unique and very important for various cosmological studies, such as constraining cosmological parameters using the measurements of the galaxy cluster mass function (see, e.g., Vikhlinin et al., 2009; Planck Collaboration, 2014a, 2015c).

Many of the clusters detected in the *Planck* survey are known galaxy clusters that were detected previously in various optical or X-ray surveys. However, about half of the detected objects turn out to be previously unknown clusters. For these objects additional optical observations should be carried out in many cases, to optically identify them with galaxy clusters and to measure their redshifts. This work is carried out at many telescopes (Planck Collaboration, 2014b, 2015a,b,d,e); our team also participates in this work.

For some of the clusters identified by our team previously, only photometric redshift estimates were reported (Planck Collaboration, 2015a). The accuracy of these estimates (about 3%) is insufficient for an accurate measurement of the cluster mass function. To make spectroscopic redshift measurements for these clusters, we carried out additional optical observations at RTT-150, the 2.2-m Calar Alto Observatory telescope, and the 6-m BTA telescope during 2014. The results of these measurements are presented below.

OBSERVATIONS

Cluster member galaxies are identified trough the observation of the red sequence of galaxies in the color-magnitude diagram. The photometric redshift estimates for clusters were previously obtained from the red sequence colors (Planck Collaboration, 2015a). To obtain a reliable cluster spectroscopic redshift measurement, it is sufficient to measure the redshift of several brightest cluster member galaxies at the cluster center, or even one brightest cluster galaxy at the

[*] e-mail: rodion@hea.iki.rssi.ru

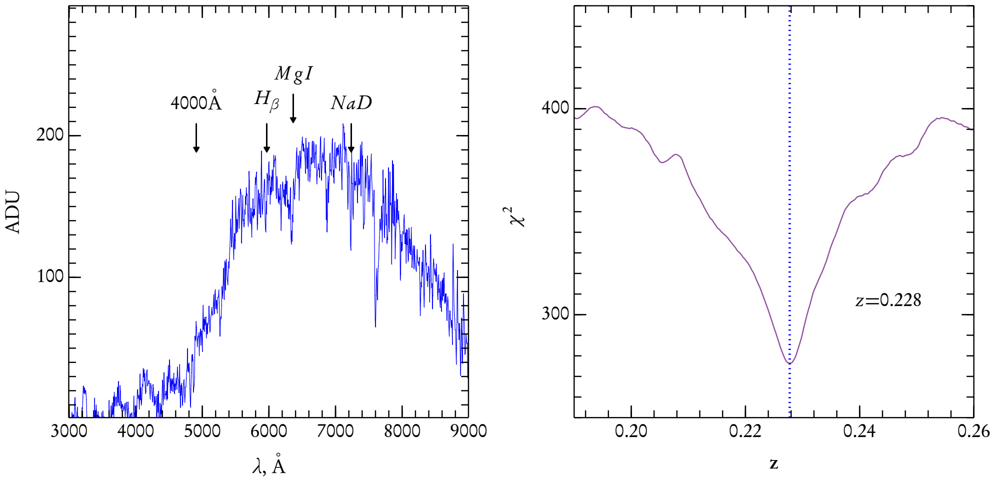

Fig. 1. The spectrum of the brightest galaxy of cluster PSZ1 G114.81−11.80, $z = 0.2277$, obtained with TFOSC spectrometer at RTT-150 telescope (left) and χ^2 from the cross-correlation with an elliptical galaxy template spectrum (right).

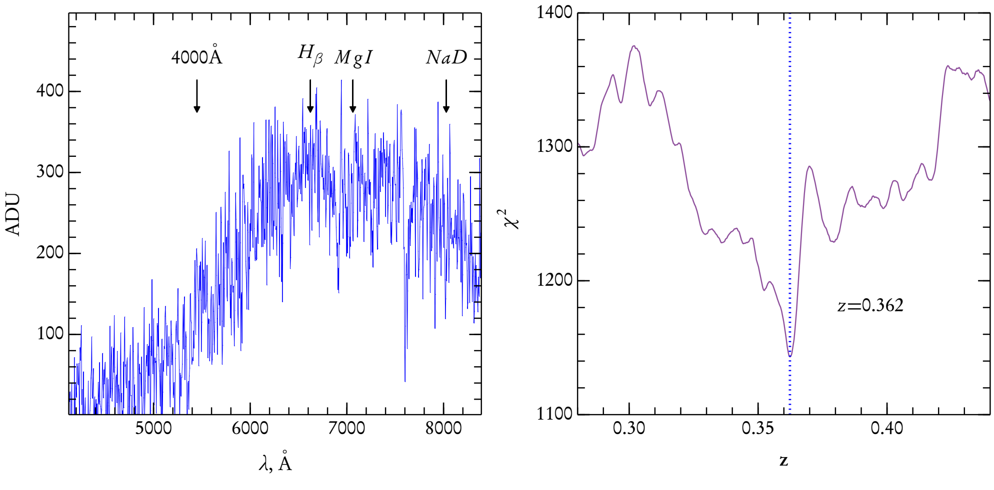

Fig. 2. The spectrum of the brightest galaxy of cluster PSZ1 G157.84+21.23, $z = 0.3623$, obtained with CAFOS spectrometer at 2.2-m Calar Alto Observatory telescope (left) and χ^2 from the cross-correlation with an elliptical galaxy template spectrum (right).

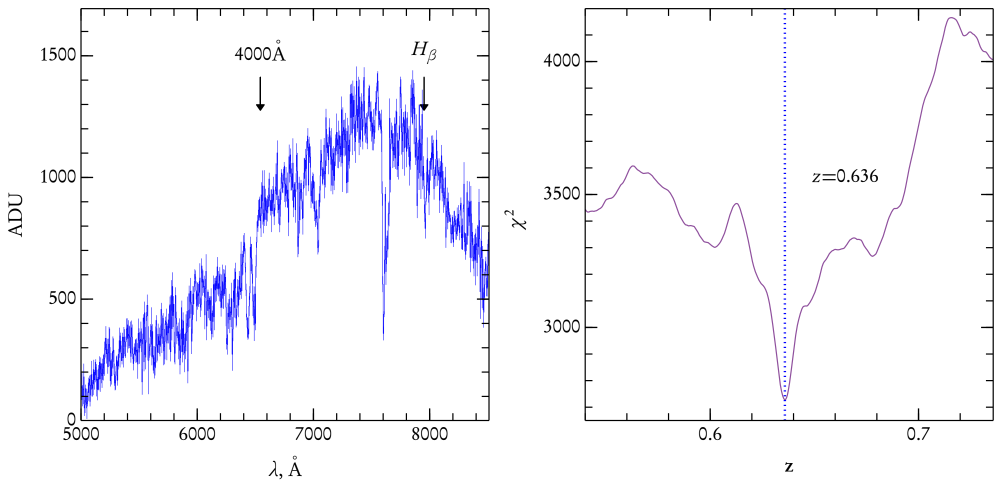

Fig. 3. The spectrum of brightest cluster's galaxy PSZ1 G183.26+12.25, $z = 0.6359$, obtained with the 6-m BTA telescope using the *SCORPIO-2* spectrometer (left) and χ^2 from the cross-correlation with an elliptical galaxy template spectrum (right).

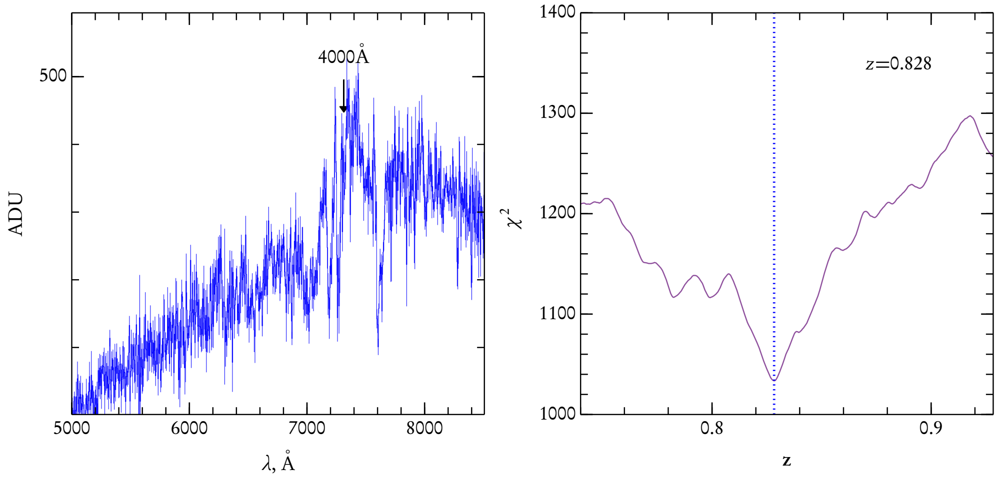

Fig. 4. The spectrum of brightest cluster's galaxy PSZ1 G141.72+14.22, $z = 0.8283$, obtained with the 6-m BTA telescope using the *SCORPIO-2* spectrometer (left), and χ^2 from the cross-correlation with an elliptical galaxy template spectrum (right).

Table 1. Redshifts of galaxy clusters

Name	Coordinates (J2000) α	δ	z	telescope*	Other name
PSZ1 G048.22−65.03	23 09 51.0	−18 19 57	0.413	2,3	
PSZ1 G060.12+11.42	18 58 46.0	+29 15 34	0.225	1	
PSZ1 G071.57−37.96	22 17 15.8	+09 03 10	0.291	1	ACO 2429
PSZ1 G080.11−77.29	00 15 24.4	−17 30 34	0.462	3	
PSZ1 G134.31−06.57	02 10 25.1	+54 34 09	0.334	3	
PSZ1 G141.73+14.22	04 41 05.8	+68 13 16	0.828	3	
PSZ1 G157.44+30.34	07 48 54.3	+59 42 06	0.403	2	[ATZ98] B100
PSZ1 G157.84+21.23	06 40 32.7	+57 45 36	0.363	2,3	
PSZ1 G183.26+12.25	06 43 09.9	+31 50 55	0.636	3	
PSZ1 G205.56−55.75	03 15 22.0	−18 12 22	0.236	1	
PSZ1 G210.55−44.61	04 03 42.5	−17 08 04	0.143	2	ACO 472
PSZ1 G223.04−20.27	05 54 37.3	−17 44 35	0.163	1	
PSZ1 G224.01−11.14	06 30 55.3	−14 51 00	0.560	3	

The telescope at which the cluster redshift was measured: 1 for the 1.5-m RTT-150 telescope; 2 for the 2.2-m Calar Alto Observatory telescope; 3 for the 6-m BTA telescope.

center of a regular cluster. Spectroscopic redshifts can be efficiently measured for galaxy clusters at $z < 0.4$ with 1.5–2-m telescopes. Larger telescopes should be used to measure the redshifts of clusters at higher z.

The procedure of cluster optical identifications and measuring their redshifts used in our work are based on those developed for *400d* X-ray survey of galaxy clusters (Burenin et al., 2007) and for *160d* survey (Vikhlinin et al., 1998) earlier. The data of WISE IR-survey (Wright et al., 2010) were used to search for distant galaxy clusters among unidentified SZ sources, as described in Burenin (2015). This procedure is described in more detail in Planck Collaboration (2015a).

Optical spectra of galaxy clusters were obtained with the RTT-150 telescope using the *TFOSC* (TÜBİTAK Faint Object Spectrograph and Camera[1]) spectrograph in longslit mode. We used grism (#15) with ≈12Å resolution in 3900–9100Å band, and 100 μm (1.8″) size slit. Spectroscopic observations presented in this paper, were done during seven nights in the end of 2013 and during 2014 year at the telescope RTT-150.

Some redshift measurements of clusters were performed with Calar Alto Observatory 2.2-m telescope using the CAFOS (Calar Alto Faint Object Spectrograph)[2] spectrograph. Observations were carried out during 4 nights in autumn, 2014. For spectroscopic measurements G-200 grism was used, which provide spectral resolution of about 10Å in 4000–8500 Å spectral band.

The spectroscopic redshift measurements for distant clusters ($z > 0.4$) were made with the 6-m SAO RAS telescope (Bolshoy Teleskop Azimutal'nyu, BTA) using the *SCORPIO-2* spectrometer (Afanasyev and Moiseev, 2005, 2011). We used volume phase holographic grating 940@600, which provide about 10Å spectral resolution in 4000–8500 Å band. To obtain spectroscopic data we used three observing nights in November, 2014, during which we were able to get about 12 hours of observational time.

The observations were carried out in approximately the same way at all telescopes. Typically, a series of two or three spectra was taken for each slit with an exposure time of 6001200 s; the spectra of flat-field and comparison lamps were also taken. During the subsequent reduction, the series of spectra for the object was aligned along the spatial axis and combined into a single spectrum for the subsequent extraction of one-dimensional spectra. All spectroscopic data were reduced with the standard `IRAF`[3] software package, which provides the tools to reduce the spectra obtained with long-slit spectroscopy, and using our own software.

It turns out that to obtain sufficiently accurate spectroscopic redshift measurements it is not required to get a very high signal-to-noise ratio spectra of elliptical galaxies. Even if individual spectral features are not detected, redshift can be measured accurately from cross-correlation with elliptical galaxy template spectrum. Accuracy of spectroscopic redshift measurements presented in this work can be estimated from delta χ^2 and by comparison with other available redshifts measurements. This accuracy is not worse than 0.5%, except for one case where the resulting spectrum is too noisy and the accuracy of z measurement

[1] http://hea.iki.rssi.ru/rtt150/
[2] http://w3.caha.es/alises/cafos/cafos22.html
[3] http://iraf.noao.edu/

is about 1% (see below).

As an example, the spectra of the brightest galaxies in clusters at various redshifts taken at RTT-150, Calar Alto Observatory 2.2-m telescope, and BTA 6-m telescope are shown in Figs. 1–4 (left panel). Right panels in these Figures show χ^2 from cross-correlation of the galaxy spectrum with template spectrum of an elliptical galaxy. The minimum of χ^2 corresponds to the most probable redshift of the elliptical galaxy.

RESULTS

The results of our spectroscopic measurements for galaxy clusters from the first catalogue are presented in Table 1. The object names, the coordinates of the cluster optical centers, and the redshifts measured here are provided in this Table. The coordinates of the cluster optical centers were taken from Planck Collaboration (2015a) and are given here for completeness. The last two columns specify which telescope was used to measure the redshift. For two clusters, PSZ1 G060.12+11.42 and PSZ1 G071.57−37.96, the redshifts were also measured at the European Northern Observatory telescopes (Planck Collaboration, 2015e), and these measurements are in good agreement with ours.

Below, we give comments on several individual objects.

PSZ1 G141.73+14.22

The measured redshift of this cluster, $z = 0.828$, in the table is considerably more accurate (the error is about 0.2%) than its redshift in Planck Collaboration (2015a). The reason is that in our work we used the spectrum of the brightest cluster galaxy measured with a considerably higher signal-to-noise ratio, which was obtained at the 6-m BTA telescope (see Fig. 4). In addition, using the 2.2-m Calar Alto Observatory telescope, we were able to obtain a considerably deeper image of this cluster (see Fig. 5), which assure the optical identification of this object.

PSZ1 G157.44+30.34

The spectrum of the brightest galaxy in this cluster taken at the 2.2-m Calar Alto Observatory telescope is noisy. Nevertheless, we estimate the error in the redshift of this object to be not larger than 1%. Larger exposure of the object is needed to make a spectroscopic measurement with an accuracy considerably better than 1%.

PSZ1 G183.26+12.25

The photometric redshift estimate $z_{\text{phot.}} = 0.85$ is given in Planck Collaboration (2015a) for this cluster. The spectroscopic redshift measured here and given in the table is remarkably different from the original photometric estimate: $z = 0.636$ (see Fig. 3). The reason is that the direct images from which the photometric z estimate was made were obtained under uncertain photometric conditions, and, apparently, these conditions actually appers to be not suitable for the photometric measurements with the required accuracy.

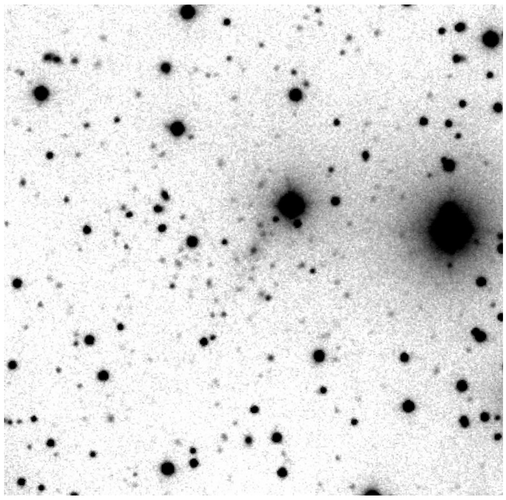

Fig. 5. Deep direct image of cluster PSZ1 G141.72+14.22 ($z = 0.8283$) in i filter, obtained at the 2.2-m Calar Alto Observatory telescope.

CONCLUSION

At present, the program of optical observations of galaxy clusters from the first *Planck* Sunyaev-Zeldovitch sources catalogue of clusters may be considered to be completed. In result of this work, 214 galaxy clusters were detected, and, thus, the first catalogue contains 947 confirmed galaxy clusters; the spectroscopic redshifts were measured for 736 of them (Planck Collaboration, 2015b). During 2011–2013, using observations at RTT150 and the 6-m BTA telescopes, our team detected 47 previously unknown clusters and measured the spectroscopic redshifts for 65 clusters (Planck Collaboration, 2015a).

In this paper, we present the spectroscopic redshift measurements for 12 more clusters; for one distant cluster (PSZ1 G141.73+14.22, $z = 0.828$), the accuracy of the redshift mesurement was improved significantly. The corresponding observations were performed during 2014 at RTT150 and 6-m BTA as well as at the 2.2-m Calar Alto Observatory telescope. Thus, the contribution of our team to the optical identification and redshift measurement of clusters from the first *Planck* catalogue is significant.

Recently, the second catalogue of galaxy SZ sources (Planck Collaboration, 2015d) was published, which includes 1653 objects, of them 1203 are confirmed galaxy clusters. Our team will continue the optical observations of clusters from this catalogue with RTT150, 6-m BTA, the Calar Alto Observatory telescopes, and, probably, other telescopes.

All clusters from the Planck survey most probably will be detected in the future Spectrum-Röentgen-Gamma (*SRG*) space observatory all-sky X-ray galaxy cluster survey. Therefore, our observations may also be considered as the beginning of work on the optical support for the future SRG/eROSITA survey.

ACKNOWLEDGEMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 13-02-12250-ofi-m). We thank TÜBITAK, the Space Research Institute, the Kazan Federal University, and the Academy of Sciences of Tatarstan for partial support in using the RussianTurkish 1.5-m telescope in Antalya (RTT150). I.F. Bikmaev, R.Ya. Zhuchkov, and A.V. Mescheryakov thank the Government of the Russian Federation for financial support through the subsidy within the framework of the Program aimed at increasing the competitiveness of the Kazan Federal University among the worlds research centers. I.M. Khamitov was supported by the subsidy provided to the Kazan Federal University to carry out a State assignment in the area of scientific activity.

REFERENCES

2. Afanasyev and Moiseev (V.L. Afanasyev, A.V. Moiseev), Astronomy Letters **31**, 194 (2005).
3. Afanasyev and Moiseev (V.L. Afanasyev, A.V. Moiseev), Balt. Astr. **20**, 363-370 (2011).
4. Burenin et al. (R.A. Burenin, A. Vikhlinin, A. Hornstrup et al.), Astrophys. J. Suppl. Ser. **172, i.2**, 561-582 (2007).
5. Burenin R.A., Astronomy Letters **41**, 167 (2015).
6. Vikhlinin et al. (A. Vikhlinin, B.R. McNamara, W. Forman et al.), Astrophys. J. **502**, 558 (1998).
7. Vikhlinin et al. (A. Vikhlinin, A.V. Kravtsov, R.A. Burenin et al.), Astrophys. J. **672, i.2**, 1060-1074 (2009).
8. Wright et al. (E.L. Wright, P.R.M. Eisenhardt,, A.K. Mainzer, M.E. Ressler, R.M. Cutri, T. Jarrett, J.D. Kirkpatrick, D. Padgett, et al.), Astron. J. **140**, 1868 (2010).
9. Planck Collaboration (Planck 2013 Results XX: P.A.R. Ade, N. Aghanim,C. Armitage-Caplan et al.), Astron. Astrophys. **571**, A20 (2014a).
10. Planck Collaboration (Planck 2013 Results XXIX: P.A.R. Ade, N. Aghanim, C. Armitage-Caplan et al.), Astron. Astrophys. **571**, A29 (2014b); arXiv:1303.5089.
11. Planck Collaboration (Planck Intemediate Results XXVI: P.A.R. Ade, N. Aghanim, M. Arnaud et al.), Astron. Astrophys., in press (2015a); arXiv:1407.6663.
12. Planck Collaboration (Planck 2013 Results XXXII: P.A.R. Ade, N. Aghanim, C. Armitage-Caplan et al.), Astron. Astrophys. **581**, A14 (2015b); arXiv:1502.00543.
13. Planck Collaboration (Planck 2015 Results XXIV: P.A.R. Ade, N. Aghanim, M. Arnaud et al.), Astron. Astrophys., in press (2015c); arXiv:1502.01597.
14. Planck Collaboration (Planck 2015 Results XXVII: P.A.R. Ade, N. Aghanim, M. Arnaud et al.), Astron. Astrophys., in press (2015d); arXiv:1502.01598.
15. Planck Collaboration (Planck Intermediate Results XXXVI: P.A.R. Ade, N. Aghanim, M. Arnaud et al.), Astron. Astrophys., in press (2015e); arXiv:1504.04583.
16. Sunyaev and Zeldovich (R.A. Sunyaev, Ya.B. Zeldovich), Comments on Astrophysics and Space Physics **4**, 173 (1972).