CFA OBSERVING TIME REQUEST

Program No.: ______

P. I.: Igor Chilingarian Trimester: 2018 May-August

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Col.: K.Grishin; A.Afanasiev; I.Katkov; I.Zolotukhin (MSU, Russia)

Program Title: Internal dynamics of recently formed ultra-diffuse galaxies

Telescope: MMT 6.5m

Instrument: Binospec

Other (multislit, ap plates, etc): 1000gpm, central wavelength 4600A

Nights Requested: D 1.3 ∎ G 0 B 0

Queued Observing: Yes X No ____ Home Phone ____

Term: long/initial ____ long/cont ____ short X engineering ____ Additional nights ____

Student Project: research exam ____ thesis ____ other ____

Acceptable Dates: May-Jun

Dates You Cannot Use: none

Targets: Number 4 Magnitude Range 17-19

Targets: RA Range 13, 16 Dec Range +28, +16

Abstract Include a short summary of your project. The summary should outline the main goals of the project and should not exceed 100 words.

Ultra-diffuse galaxies (UDGs) is a recently identified galaxy type: they have sizes comparable to the Milky Way and stellar masses of about 1/1000 of it. UDGs attracted a lot of attention as possible "dark galaxies" heavily dominated by dark matter, however, no dynamical mass estimates were done because of their extremely low surface brightness. We have recently found 13 diffuse blue post-starburst (300-500Myr) galaxies without ongoing star formation in Coma and Abell2197, which, should they continue to evolve passively, will become UDGs in 5Gyr. We propose to obtain their kinematic profiles using Binospec. These observations will potentially solve the UDG formation puzzle.

1 Scientific Justification

Ultra-diffuse galaxies (UDG; van Dokkum et al. 2015a) were identified from deep ground-based observations performed with the Dragonfly telescope array (Abraham & van Dokkum 2014) as extended ($r_e > 1.5$ kpc) low surface brightness ($\mu_{0,g} > 24$ mag arcsec^{-2}) galaxies populating the Coma cluster. With the sizes comparable or sometimes exceeding the Milky Way size, these galaxies have stellar masses of 0.1%−1% that of the Galaxy. The initial sample of 47 Coma UDGs grew to 854 (Koda et al. 2015) found in deep Subaru Suprime-Cam images, 271 of which turned to be larger than the Milky Way. Later, UDGs were detected in other galaxy clusters and groups (see Appendix A in Yagi et al. 2016). All Coma cluster UDGs have integrated colors compatible with old passively evolving stellar populations (Koda et al. 2015).

Extremely low surface brightness levels in UDGs prevent their efficient studies using ground based spectroscopy. Only a few UDGs have spectroscopic measurements of their radial velocities confirming their Coma cluster membership (van Dokkum et al. 2015b; Kadowaki et al. 2017), but no stellar velocity dispersion measurements have been carried out so far. UDGs are hypothesized to be heavily (98%-99%; van Dokkum et al. 2015a, Koda et al. 2015) dark matter dominated and sometimes even called “dark galaxies” even though no internal dynamics measurements can confirm this claim. The formation mechanisms for UDGs remain purely speculative because no observational data can confirm/refute any scenario (slow star formation in a shallow primordial dark matter potential well, interstellar medium (ISM) stripping from disky progenitors by SN feedback and/or ram pressure, star formation quenching by tidal stirring in a cluster, etc.)

The only “easy” option on the table is to find UDGs in the early stage of evolution when their stars are still young and, therefore, the surface brightness is comparable to that in normal disk galaxies. Recently, we have identified a sample of 13 very unusual blue extended diffuse post-starburst (PSG) galaxies in the Sloan Digital Sky Survey DR7 (Abazajian et al. 2009) using our stellar population analysis presented in the Reference Catalog of Spectral Energy Distributions (RCSED, Chilingarian et al. 2017). This sample includes all galaxies in the SDSS primary sample with Hα emission not exceeding the 10σ detection in order to exclude star forming objects, simple stellar population ages younger than 2 Gyr and the k-corrected color $g - r < 0.55$ mag. 10 of 13 galaxies turned to be Coma cluster members, 2 others are hosted by the double galaxy cluster Abell 2147/2197, and 1 is in the compact galaxy group SDSSCGA 01018.

We retrieved archival optical images from the Canada-France-Hawaiian Telescope and Subaru for 12 cluster galaxies and near-infrared Spitzer Space Telescope images at 3.6, 4.5, 5.8, and 8μm for 10 Coma galaxies. All of them have effective radii between 1.8 and 4.0 kpc, quite regular morphologies, mean stellar ages between 300 and 750 Myr and central surface brightness levels about μ_0, g=20.5–22.0 mag arcsec$^-2$. Most of them are strongly flattened suggesting their disky morphology. If those objects continue to evolve passively in 5–7 Gyr they will all end up as UDGs because their surface brightness will decrease by 2–4 mag/arcsec$^-2$. Two galaxies have archival HST images where complex shell structures are seen suggesting that the galaxies experienced strong star burst episodes before they have been stripped.

Three galaxies in Coma exhibit prominent straight tails up-to 250 kpc long supposedly formed by the material stripped by the ram pressure (Gunn & Gott 1972). Only the brightest and largest galaxy is detected at 5.8μm, none is detected at 8μm and two longer WISE bands

(12 and 22μm) which supports our claim of the lack of star formation based on optical spectra. Our novel spectrophotometric fitting technique NBursts+phot (Chilingarian & Katkov 2012) uses SDSS spectra simultaneously with the FUV-to-NIR broadband photometry and allows us to robustly disentangle young recently formed stars and old underlying stellar population. None of our galaxies is dominated by old stars by mass, therefore our estimates of the surface brightness dimming as a result of passive evolution must be valid.

The 13 blue diffuse PSGs suggest that the UDGs are normal low surface brightness disk galaxies which had been slowly forming stars until they entered the central region of a galaxy cluster, where the ram pressure compressed the ISM and induced a short but intense burst of star formation until it was quenched by the increasing ram pressure that swept away the remaining ISM to the intracluster space.

The SDSS spectra have insufficient spectral resolution to confidently measure internal velocity dispersion and estimate dynamical masses and also lack spatial information. Obtaining spatially resolved major axis kinematics (v, σ) and stellar populations (age, [Fe/H]) will allow us to answer the following questions: (a) are they dark matter dominated? (b) are they rotationally supported? (c) do they have positive stellar age and negative metallicity gradients consistent with outside-in ram pressure stripping scenario? If the answers are "no" to the first and "yes" to the second and third question, we will solve the UDG formation puzzle.

2 Experimental Design

Our goal is to observe the complete sample of 13 SDSS selected diffuse PSGs. Because 12 of 13 galaxies are hosted in rich cluster, we can use the MOS capability of Binospec in order to observe more than 1 object at a time using tilted slits. In June/2017 we had a Fast Turnaround program approved at Gemini-North and obtained data for one galaxy (3.2h integration time; 1200gpm grating, R=2700). We successfully reconstructed major axis kinematics and stellar populations and proved the feasibility of our project. Binospec has better throughput in the blue and also slightly higher spectral resolution with the 1000gpm grating. In fact, we observed 2 targets in Dec/2017 with Binospec in one mask with tilted slits and proved that in 1h20min we have comparable integration to 2.5h with GMOS.

In 2018A we propose to obtain deep long-slit spectra of 8 blue diffuse PSGs: 6 in the Coma cluster (3 masks) and 2 in Abell 2147/2197 (1 mask) using the MMT Binospec spectrograph with the 1000gpm grating centered at 4600 Å and a 1-arcsec-wide slit. The requested setup will provide us the R=4500 resolving power which will allow us (for a signal-to-noise ratio of 12-15 per pixel) to reliably measure velocity dispersions down to $\sigma = 15$ km/s and radial velocities as accurate as 2 km/s and, therefore, perform the dynamical modeling of our galaxies even in the dark matter free case, where we expect $\sigma \sim 30$ km/s. We expect that we will reach S/N=15 in 2.5 hours of integration on dark sky. The requested setup will cover the wavelength range containing a lot of weak metal lines which will provide a handle on the stellar age/metallicity and will allow us to detect and measure stellar population gradients.

We request an eqiuvalent of 1.3 nights (10h + overhead) in the queue mode. As a special calibration we will need high signal-to-noise spectral twilight flats to be taken in the requested Binospec setup. The availability of flux calibrated SDSS spectra will allow us to easily calibrate our data without observing spectrophotometric standards for every object.

3 Figures

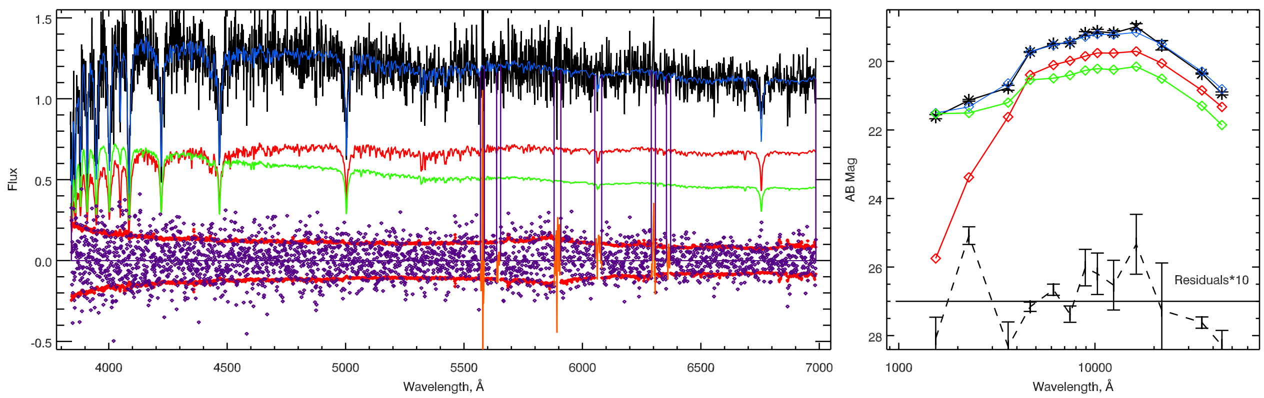

Figure 1: An example of a full spectrophotometric fitting of a Coma diffuse blue PSG (objid=587741602572730542) using the NBursts+phot technique. The spectrum is represented by 2 simple stellar populations: t=1 Gyr, [Fe/H]=-0.51 dex (red) and t=120 Myr, [Fe/H]=-0.3 dex (green). The left panel shows the SDSS spectrum, the right panel presents the broadband SED which includes GALEX FUV/NUV, SDSS *ugriz*, UKIDSS *YJHK*, and Spitzer IRAC1/2 measurements in a 3 arcsec aperture centered on the galaxy, which corresponds to the SDSS fiber.

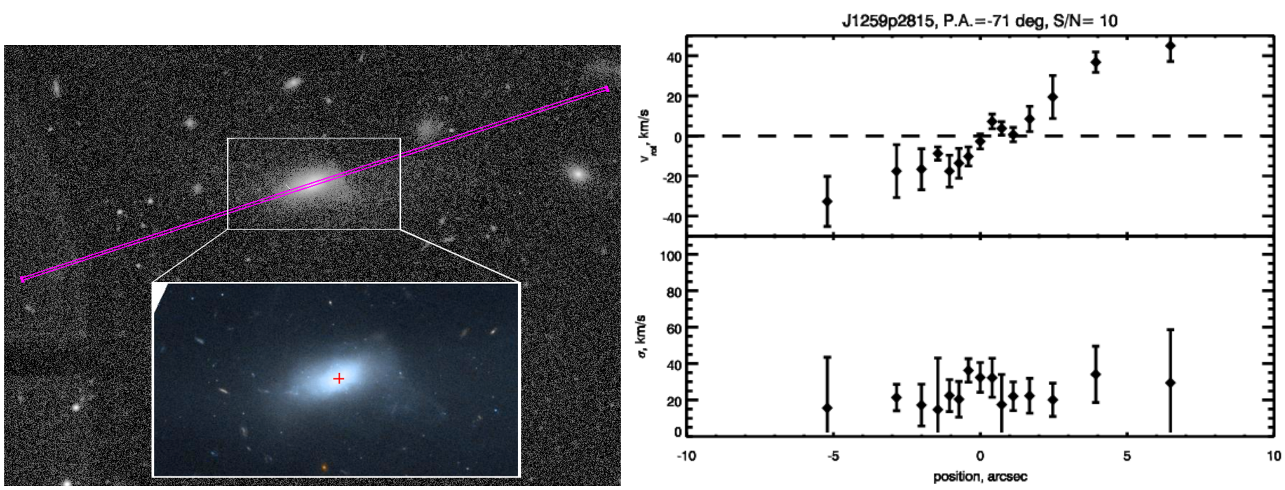

Figure 2: A blue post-starburst galaxy J1259+2815 observed with GMOS (left) and its recovered internal kinematics (right): radial velocity profile and velocity dispersion. According to the preliminary results of dynamical modelling done by a student (A.Afanasiev), the kinematics is consistent with the dynamical M/L ratio of 1.1 in the V bands in Solar units, which suggests very little dark matter at best.

4 Progress of the continuing project

4 nights allocated in Jul/2017 on BlueChannel, 100% lost to weather. 4h allocated at GMOS@Gemini-North as a fast turnaround program (N2017A-FT-22), data reduced and analysed; 1.3h of Binospec (2017C) – reduced.

5 Previous OIR time awards and relevant publications

- Distant galaxies: 6 nights with MMIRS@Magellan in 2014B/2015A (3 nights lost to instrument) – data reduced and analysed, **1 paper published + 2 in prep**; 20 nights with MMIRS@MMT in 2015C-2017C (9 lost) – data reduced; analysis in progress;
- LCO Stellar Library: 26 nights allocated in 2013A-2017A at Magellan; observatons finished; **2 papers in prep**; 4 conference presentations; FIRE data reduction pipeline developed; data reduction in progress
- LMC Star Clusters: 2 nights with MagE@Magellan in 2016B **1 paper submitted**
- Intermediate mass black hole confirmation: 3 half-nights of DDT using MagE@Magellan in Jul-Aug/2017; **1 paper submitted + 1 in prep**

Relevant Publications: Data Analysis, Big Data Approach

1. Chilingarian I., Zolotukhin I., Katkov I., Melchior A.-L., Rubtsov E., **Grishin K.**, 2017, ApJS, 228 14: *RCSED – A Value-added Reference Catalog of Spectral Energy Distributions of 800,299 Galaxies in 11 Ultraviolet, Optical, and Near-infrared Bands: Morphologies, Colors, Ionized Gas, and Stellar Population Properties*
2. Chilingarian I. et al. 2007, proc. of IAUS 241, 175: *NBursts: Simultaneous Extraction of Internal Kinematics and Parametrized SFH from Integrated Light Spectra*
3. Chilingarian I., Katkov I. 2012, proc. of IAUS 284, 26: *NBursts+phot: parametric recovery of galaxy SFHs from the simultaneous fitting of spectra and broad-band spectral energy distributions*
4. Chilingarian I. 2009, MNRAS, 394 1229: *Evolution of dwarf early-type galaxies - I. Spatially resolved stellar populations and internal kinematics of Virgo cluster dE/dS0 galaxies*
5. Chilingarian I. & **Zolotukhin I**, 2015 Science 348 418: *Isolated compact elliptical galaxies: Stellar systems that ran away*

6 Description of Collaboration

IC serves as a PI. He discovered diffuse blue PSGs and developed the major part of the NBursts+phot spectrophotometric fitting technique. IC plans observations and leads the data reduction. He also coordinates the collaboration between CfA and Moscow State University (Russia). **KG** is an undergraduate student in Moscow, a co-author of the RCSED catalog paper; he is currently responsible for collecting and processing archival photometric data from CFHT, Subaru, Spitzer, and HST. He performs 1D and 2D light profile decomposition of galaxy images. **AA** is a MSc student in Moscow, he is responsible for dynamical modelling. **IK** contributed to the NBursts+phot development and will analyze the data. **IZ** connects the ram pressure stripping efficiency to X-ray properties of the clusters (e.g. positions of shock fronts)

7 Target List

Target	R.A.(J2000) n	Dec (J2000)	Mag (r)	Host Cluster
SDSS J160154.20+160016.7	16:01:54.20	+16:00:16.7	17.3	Abell 2147/97
SDSS J125842.58+274537.7	12:58:42.58	+27:45:37.7	16.7	Coma
SDSS J125832.28+282240.7	12:58:32.28	+28:22:40.7	17.1	Coma
SDSS J125624.46+294817.7	12:56:24.46	+29:48:17.7	17.5	Coma

8 References

Abazajian et al. 2009, ApJS 182 543: *The Seventh Data Release of the Sloan Digital Sky Survey*

Abraham & van Dokkum 2014, PASP 126 55: *Ultra-Low Surface Brightness Imaging with the Dragonfly Telephoto Array*

Chilingarian & Katkov 2012 IAUS 284 26: *NBursts+phot: parametric recovery of galaxy star formation histories from the simultaneous fitting of spectra and broad-band spectral energy distributions*

Chilingarian et al. 2017, ApJS 228 14: *RCSED: A Value-added Reference Catalog of Spectral Energy Distributions of 800,299 Galaxies in 11 Ultraviolet, Optical, and Near-infrared Bands: Morphologies, Colors, Ionized Gas, and Stellar Population Properties*

Gunn & Gott 1972, ApJ 176 1: *On the Infall of Matter Into Clusters of Galaxies and Some Effects on Their Evolution*

Kadowaki et al. 2017, ApJ 838 21: *Spectroscopy of Ultra-diffuse Galaxies in the Coma Cluster*

Koda et al. 2015, ApJ 807L 2: *Approximately a Thousand Ultra-diffuse Galaxies in the Coma Cluster*

van Dokkum et al. 2015a, ApJ 798L 45: *Forty-seven Milky Way-sized, Extremely Diffuse Galaxies in the Coma Cluster*

van Dokkum et al. 2015b, ApJ 804 30: *Spectroscopic Confirmation of the Existence of Large, Diffuse Galaxies in the Coma Cluster*

Yagi et al. 2016, ApJS 225 11: *Catalog of Ultra-diffuse Galaxies in the Coma Clusters from Subaru Imaging Data*