A Kinematic Study of IC 225, Gemini Multi Object Spectrograph Integral Field Unit Data of a Dual-Nuclei Dwarf Elliptical Galaxy

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ABSTRACT

We present the preliminary findings of a kinematic study of the low luminosity elliptical galaxy IC 225. This object is of considerable interest as it contains two bright nuclei which could give cadence to the theory of Dwarf Elliptical (dE) formation through merger scenario. We present Integral Field Unit (IFU) data of the dE from the Gemini-North Multi Object Spectrograph (GMOS) Integral Field Unit (IFU) taken December of 2005. This paper consists largely of technical information about the reduction process; and we present a new comprehensive reduction plan for data of this sort. From the reduced IFU data, we present several 2D maps of the region including higher order Balmer lines and the [OIII] couplet at $\lambda\lambda$4959, 5007. From these images we conclude that within IC 225, the off-center nucleus is almost certainly assocaited with a large cloud of gas. Preliminary kinematic evidence of net rotation within the gas of the galaxy is also presented along with evidence of some stellar movement.

Subject headings: galaxies: dwarf — galaxies: individual (IC 225) — galaxies: kinematics and dynamics — galaxies: formation — technical: Gemini Multi Object Spectrograph Integral Field Unit

1. Introduction

Low luminosity elliptical galaxies are the most common type of galaxies found in the local universe. These galaxies, often referred to as dwarf ellipticals (dEs), are characterized by blue absolute magnitudes greater than M_B = - 18 (Lotz et al. 2004) and by the smoothness of their surface-brightness profiles (Ferguson & Binggeli 1994). dEs are also largely devoid of gas and often have old stellar populations (greater than several billion years) (Lotz et al. 2004). Most dEs show multiple stages of star formation. These ellipticals are usually satellites to much more massive local galaxies or are found in the high density central regions of large galaxy clusters. dEs have widely varying internal structures and dynamics including bright stellar nuclei (Lotz et al. 2004), disk, bar, and spiral structures (see De Rijcke et al. 2004 and references therein), and kinematically decoupled cores (De Rijcke et al. 2004).

The study of dEs began in 1938 when Shapley discovered two dE companion galaxies to the Milky Way (Shapley 1938). Today the importance of these widely-varying galaxies cannot be denied. The nature, formation, and evolution of dEs have and will continue to provide important constraints for both cosmological models and the galaxy luminosity function. However, dEs are perhaps the least understood and most poorly studied of all types of galaxies likely because their low luminosity, low effective surface brightness ($\mu_{Veff>}$ 22) and diffuse appearance make them difficult to observe (Ferguson & Binggeli 1994).

There exists considerable speculation as to the formation of dEs. According to hierarchical models, primordial dEs may have been the building blocks of more-massive galaxies. In these models, dEs form from slight density fluctuations in the early universe. One important epoch in hierarchical models is the cessation of star formation. There are several models for this, most of which involve the clearing of gas from the dE. Perhaps the most widely cited mechanism is supernovae driven winds which heat the interstellar gas beyond the limit of escape velocity for the galaxy. This clears out the remaining gas from the centers of dEs, thus ending the period of star formation. Others believe the gas is stripped from dEs during dynamical interactions with their larger galaxy companions. From this model, dEs are expected to be homogeneously spread out throughout the universe (see Ferguson & Binggeli 1994 and references therein). However, observations have shown that to the contrary, dEs are more commonly found in dense clusters. Other currently popular models are those in which dEs form from a progenitor population of other types of galaxies. In these scenarios, spiral and irregular galaxies are transformed into low luminosity ellipticals through interactions with other local galaxies. These models can account for the occurrence of bright stellar nuclei in dEs. The process of galaxy harassment could potentially also explain some of the irregular kinematic patterns found within dEs (Geha et al. 2002; De Rijcke et al. 2005). Other models exist in which dEs form by mergers or from tidal debris left over from massive galaxy collisions (see Lotz et al. 2001).

In many bright dEs, there exist central stellar nuclei. These, like the galaxies they belong to, are also poorly understood. In contrast to there more massive counterparts, dE nuclei are commonly far bluer than the rest of the galaxy; however, the color of the nuclei usually correlate to the predominant galactic color (Lotz et al. 2004). Although, it should be noted that both blue and red nuclei have been found (Chaboyer et al. 1994). The stellar populations of many dE nuclei are extremely similar to those of globular clusters in the region especially in terms of color. In one theory of nuclei formation, large gravitationally bound globular clusters sink to the center of dEs and eventually create the nucleus. Another nuclei formation theory argues that the higher potential wells of bright nucleated dEs could retain more gas which would allow for continued star formation in the center of the galaxy (Lotz et al. 2004). However, there is also evidence of more recent star formation in dEs. In a recent study of 69 dE galaxies, Lotz et al. discovered two blue nucleated dEs that must contain a distinct recent star formation epoch as they are constrained to ages of 1 Gyr or less (2004).

The internal kinematics of dEs are also widely varying including some exotic phenomenon such as kinematically decoupled cores (De Rijcke et al. 2004). The rotation curves of dEs are commonly quite flat, many showing no signs of any substantial organized rotation about the major axis of the galaxy. Thus, most dwarf ellipticals can not be supported by rotation and must instead rely on velocity anisotropy (Geha et al. 2002). However, while non-rotating dEs are more numerous, rotating dEs are not uncommon. Geha et al. conclude that despite the clear difference in internal kinematics, the properties (morphology, stellar populations, and environment) of these two subtypes of dEs are none-the-less quite similar (2003). The internal kinematics of exotic dEs may hold clues as to the formation of all low luminosity ellipticals. Some formation scenarios of dwarf ellipticals include formation through nuclear star burst or by mergers between globular clusters (Lotz et al. 2001). In more massive galaxies, the formation of kinematically decoupled cores (KDC) has been proposed as the result of the merger of unequal mass dEs (Geha et al. 2005). De Rijcke et al. who first discovered KDCs within dwarfs comments that in the two known cases it is more likely that the KDC formed by flyby interaction with a more massive galaxy, rather than by a merger scenario (2004). In this case dEs could form from harassed spirals; however, the internal dynamics of dEs are poorly understood leaving the possibility of formation through mergers.

In this paper, we discuss the case of one exotic dE. IC 225 is the first discovered metal-rich HII region in a dE (Gu et al. 2006) and one of two known dEs with dual nuclei (Gu et al. 2006; Zhao et al. 2006). See Figures 1 and 2. IC 225 is a recently-investigated, luminous, nearby, blue dwarf elliptical with a redshift of .00512 (20.6 Mpc) and an absolute magnitude of M_B = -17.14. The first intensive study of the object (Gu et al. 2006) classifies the galaxy as an isolated, nucleated dE. IC 225 has smooth outer isophotes and its spectrum exhibits strong, narrow, nebular emission features similar to metal-rich HII regions with the strongest emission appearing in the nuclear region. Balmer emission lines (Hα, Hβ, Hγ), [OIII] $\lambda\lambda$4959, 5007, [NII] $\lambda\lambda$6548,6583, and [SII] $\lambda\lambda$6716, 6732 are noted by Augarde et al. (1994) and Gu et al. (2006). Gu et al. also note the absence of HI gas within the galaxy and a recent epoch of starburst (6-7 x 10^6 yr) found within the central 4-5" of the galaxy(2006). The galaxy has a high metallicity [12 + log(O/H) = 8.98], especially when compared to the metallicity-luminosity relation of typical dEs (Gu et al. 2006).

Perhaps the most remarkable property of IC 225 is the presence of 2 nuclei. The central two arcseconds of the galaxy are especially blue, and within the region lie 2 nuclei spaced 1".4 apart. The off-center nucleus is far bluer than the nucleus found at the geometric center, and within the spectra, the higher order Balmer emission lines are notably blue shifted (0.5 Å) in comparison to the absorption. See Figure 3. Thus Gu et al. suggests that the absorption is associated with the nucleus at the geometric center while the emission emanates from the off-center nucleus which they propose to be an HII region with a different radial velocity (2006).

In this paper, we present preliminary results from our analysis of two-dimensional spectral data of IC 225. At this stage, our data suggests the presence of a large gaseous region centered around the off-center nucleus. Some organized rotation can be observed in the emission line velocity fields. In §2 we discuss particulars of the two-dimensional spectroscopy of IC 225. In §3, we present a general look at the reduction procedure for the Gemini Multi Object Spectrograph (GMOS) Integral Field Unit (IFU). Preliminary results of our study including two-dimensional maps of continuum, [OIII], and higher order Balmer lines, as well as velocity fields for both emission and absorbtion fields are presented in §4 and we draw conclusions in §5 and discuss the future of the project.

2. Observations

Two dimensional spectra of IC 225 were taken on the nights of December 5th, 22nd, and 23rd using the Gemini North GMOS IFU. Four 3300 second exposures were taken in two slit mode using the B600 grating and g-filter. The exposures were taken with two wavelength settings in order to dither the spectral range. The wavelength setting used had

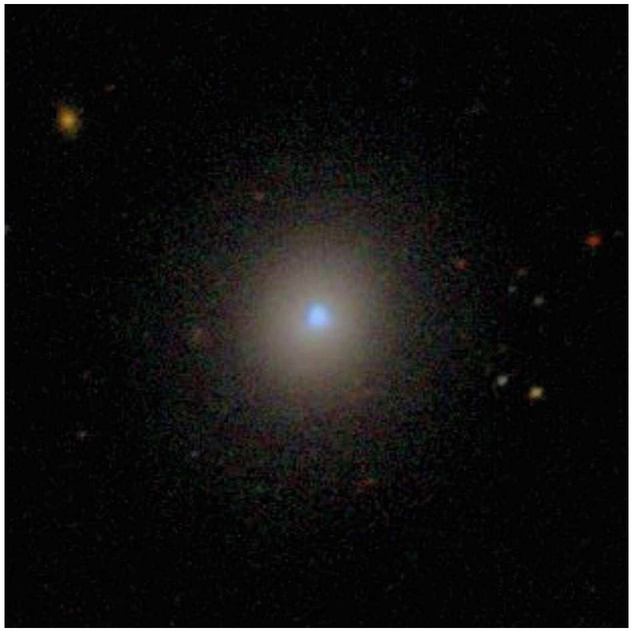

Fig. 1.— SDSS color image of IC 225 from Gu et al. (2006). The image scale is 2'x 2'. Note the typical red coloring of the galaxy and the bright blue nucleus.

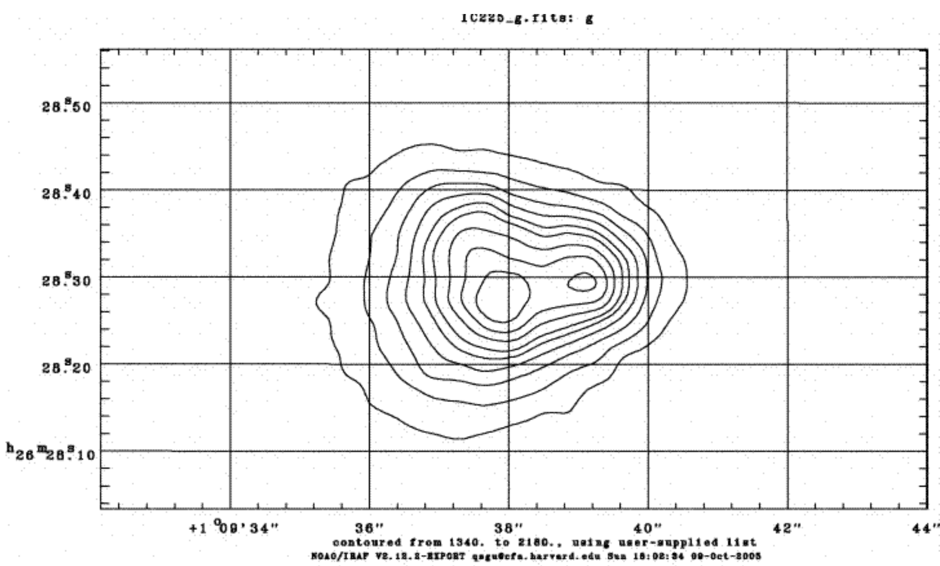

Fig. 2.— Countour plot of IC 225 from a SDSS g-band image from Gu et al. (2006). Note the two prominent nuclei. The more luminous source is positioned at the geometric center of the galaxy, while the other source is off-center and considerably bluer.

central wavelengths of 482 nm and 478 nm giving a wavelength coverage of 4200-5400 Å. The data were reduced using the procedure outlined in §3.

3. Data Reduction of GMOS IFU Spectra

The Gemini IFU is composed of 1500 individual hexagonal lenselets. In two slit mode, the IFU samples an area of 5"x 7"around the science target and an additional 5"x 3.5"sky field located 1'from the field. The lenselets each collect light which is then sent through one of two slits on GMOS. The IFU data format, while complicated, provides various benefits. The data is stored as a Multi Extension Fits (MEF) file which can be manipulated by the Gemini IRAF package. [3] This formatting is especially important as it conserves the spatial information associated with each of the fibers on the IFU array. Another important feature of IFU MEFs is the use of various data planes. The science data is stored as an extension within the MEF, however, there are also variance and data quality planes which are used during the reduction and analysis processes.

Standard spectral reduction such as flat fielding, wavelength calibrating, etc is performed using the IRAF task IFUPROC by B. Miller. Following these steps, slight velocity dispersion between data from the two different slits must be corrected through simple statistics on the arcs. The cause of this difference is currently poorly understood but is thought to be caused by the optics of the instrument and likely is caused by a difference in the way in which the spectrograph is illuminated by the two slits.

Following IFUPROC, the spectra can be sky subtracted. All of these steps are performed while the data is still two-dimensional (λ vs. fiber number). Once the previous

[3]The Gemini IRAF packages are available at:
http://www.gemini.edu/sciops/data/dataSoftware.html

steps are accomplished, the 2D data can be converted into 3D data “cubes”which have spatial axis along x and y and the spectral axis along z. During this step, the hexagonal “footprint”of each fiber is pixilated and the resulting x-y planes within the cube can be thought of as images of the target taken in exceptionally narrow filters. The Gemini IRAF task that performs these manipulations, GFCUBE, currently can not support MEFs. Thus, the data must be broken into simple fits files, gfcubed, and then rewritten into an MEF.

At this point, data which is dithered in both the spectral and special dimension can be combined. Currently the cubes must be aligned in the spatial direction by hand. There are no current IRAF packages that shift 3D spectra in the spatial direction. Thus, each 3D extension of the MEF (x,y,z) had to be broken into z 2D images of dimensions x by y. These images must be copied into larger 2D images to conserve information when they are shifted. Then the 2D planes can be shifted, recompiled into a 3D data cube and then written to a MEF.

GMOS data is taken using a 3 chip mosaic, thus spectra taken in two-slit IFU mode have gaps in one of two locations along the spectral axis. This issue can be resolved by the use of two wavelength settings with different central wavelengths. In order to accommodate both spectral and spatial dithers, the IRAF task GSCOMBINE by B. Miller had to be edited. This new version of GSCOMBINE is especially effective, because it uses the data quality plane to inform the combine feature of the location of the spectral chip gaps. Thus, the resulting spectra are quite clean.

During the reduction process, we found it useful to have a 3D spectra cropping tool. We have created the IRAF task SCROP which crops an input data cube along the spectral direction given a desired wavelength section. This is especially useful for creating 2D images that map the data in a given spectral region.

After they were reduced, the data was rebinned using Cappellari and Copin’s Voronoi

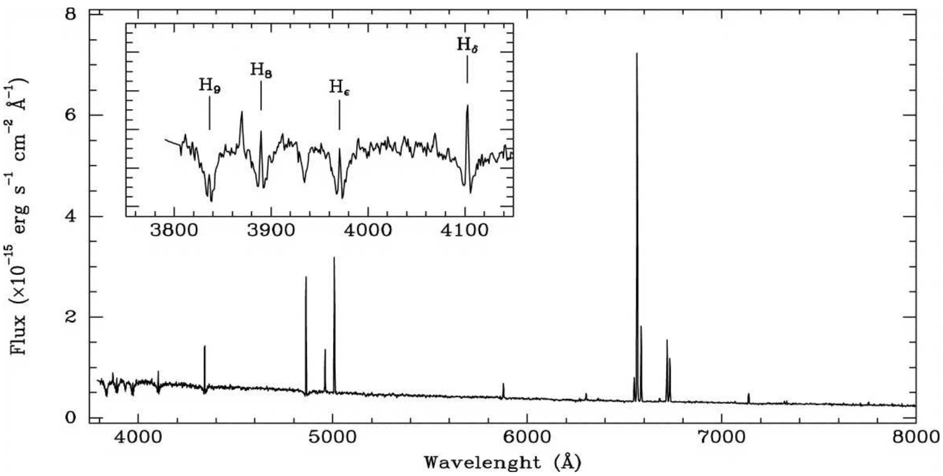

Fig. 3.— Example spectrum of IC 225 from Gu et al. (2006). Taken in the center 3 arcsec of the galaxy with SDSS. Note the narrow emission lines slightly blue-shifted from the absorbtion features.

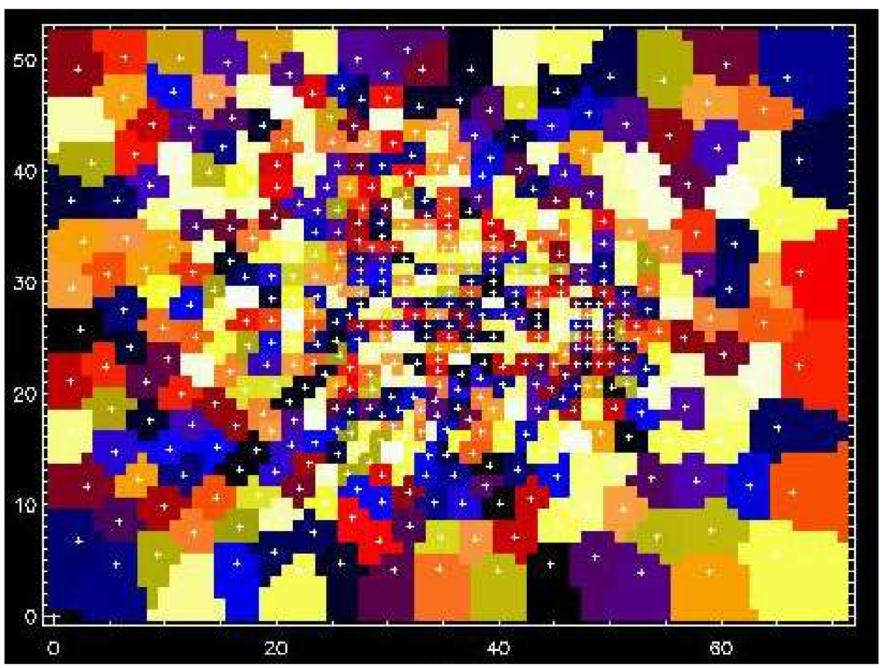

Fig. 4.— A Map of the bins created by the IDL Voronoi 2D binning procedure. S/N $\sim$ 15.

2D binning procedure to a S/N $\sim$ 15 for emission fields and $\sim$ 30 for absorption fields (Cappellari & Copin 2003) [4].

4. Preliminary Results

Following the reduction, two-dimensional maps of IC 225 were made. Using SCROP (see §3) we cropped the data cube to several specific wavelength ranges and then collapsed the spectral axis using IMCOMBINE's project feature. The resultant image is a 2D image of the galaxy taken in a specific wavelength range. This is similar to taking images in different filters. Figure 7 shows the resulting images. In Image A, the continuum image, you can see quite clearly the two nuclei. We also note that in the emission line, the off-center nucleus is much more luminous. We thus conclude that the off-center nucleus must have a significant emitting gaseous region associated with it.

From the Contiuum image in Figure 7A, we have created a contour image. This is helpful to use for future visualizations including velocity fields.

Relative velocity information was computed for the emission from the field using the NOAO RV IRAF task fxcor. This was performed on the S/N $\sim$ 15 binned spectra. The template spectrum used in this case was a high S/N 1D spectrum from the data cube. Thus, the velocity field is relative. As you can see in Figure 9 there is some organized rotation around the nucleus located at the geometric center of the galaxy. Emission features are associated with the gas in the galaxy, so we can assume that there is a net rotation of the gas within IC 225.

[4] The Voronoi 2D Binning IDL script can be found at http://www.strw.leidenuniv.nl/~mcappell/idl/#binning

Line of sight velocity information for the absorbtion features in IC22 was obtained using Michele Cappellari's Penalized Pixel-Fitting method (pPXF) (Cappellari & Emsellem 2004)[5]. SSP model spectrum from the MILES catalogue were used in the fitting procedure (Vazdekis, A. 2006). The MILES catalogue is an empirical stellar spectral library which has excellent stellar parameter coverage. The S/N $\sim$ 30 binned galaxy spectra were also inputed. pPXF is based off the Bounded-Variables Least-Squares algorithum written by Lawson & Hanson (1995). The IDL routing takes in model spectra of different ages and weights them in order to create a best fit stellar spectrum. The real power of pPXF; however, is is ability to differentiate emission and absorbtion features (see Figure 10).

The results of pPXF have been ploted in Figure 11. This plot is representative of the velocity patterns found within the absorbtion features of the galaxy sepctra. Thus, the field is the rotation of the stars within the galaxy. As noted in the figure caption, the main motion within the frame appears to be associated with the off-center nucleus. It appears that there is no net rotation of the stars associated with the main part of the galaxy. Thus, it is interesting that there is a stellar population associated with the blue off-center nucleus which is moving independently of both the other stellar field and the gas field.

5. Preliminary Conclusions and Future Work

From the 2D images which map the emission features in the galaxy, it is clear that there is a large cloud of metal rich gas associated with the off-center jump in luminosity. The velocity fields from absorbtion show stellar movement in the same region. It should be noted that while the area shows signifigant emmission from the local gas, there is little to

[5]The pPXF script can be found at http://www.strw.leidenuniv.nl/~mcappell/idl/#ppxf

no detected motion of the gas in the region. There is, however, an evident velocity pattern centered around the geometrically-centered nucleus.

From these preliminary conclutions it is evident that IC 225 merits continued study. Important imformation can still be gained from the IFU data. The velocity fields in this paper represent a first, some-what-crude analysis of the spectra. A finer fit can no doubt be obtained through careful work with the IDL routine pPXF. Additionally, the emission line velocity field will be greatly improved when the best fit stellar spectrum from pPXF is subracted before the fit. Additionally, the current emission velocity field is relative to the cube. This data would be far more meaningful if it were compared to template spectra such as those used in pPXF.

Additional information about the stellar popluations within the galaxy can be obtained from the IFU data, especially the Voronoi rebinned spectra. Ideally, information about the gas such as metalicity and and extinction would also be computed. Given this analysis, it would be much more feasible to make real conclutions as to the formation and structure of IC 225. At this time we do not have enough information to conclude on the formation of the dE.

I would like to acknowledge the direct and indirect contributions of several individuals to this project. First and foremost, many thanks go to B. Miller, my advisor. Thank you for giving me the opportunity to learn from you. This experience had been informative, challenging, and very rewarding. Thank you also, S. Kafka, REU Program Director/ REU mom extrodinare. Thank you for all of your support and for giving me this opportunity. And especially thank you for supporting me throughout my injury and recovery. I am forever indebted to my parents without whom I would not be studying science. Thank you for always believing in me. Words can not express the gratitude I have for my fellow REU students. I have learned as much from them as I have learned from all the other astronomers here at Tololo. Thank you all for supporting me during my injury and for keeping me laughing. Thanks to the technical staff here at Tololo for helping with the various comouter glitches etc. Thanks especially to P. Garagorri for your tireless help. Thanks to AURA, Gemini, and CTIO for hosting me here and to all of their employies for making me so at home. Thanks also to the National Science Foundation for funding this program. Finally, thanks to the medical staff at Clinica Las Condes, in Santiago, to Jenny Diaz and Andrea Gantz. Without the medical support of these individuals I would not have been able to continue my work here at CTIO.

Facilities: Gemini (GMOS IFU).

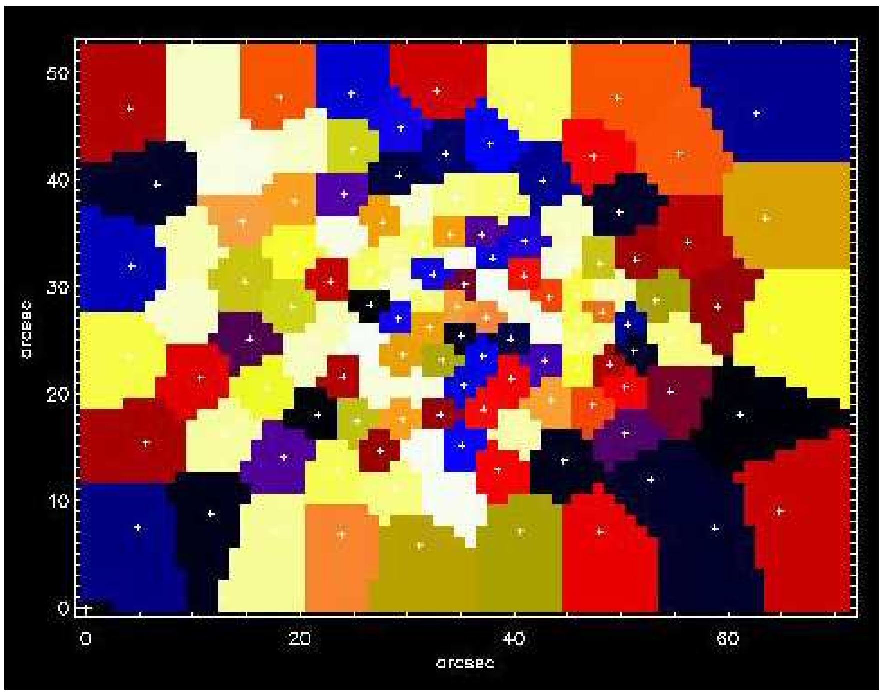

Fig. 5.— A Map of the bins created by the IDL Voronoi 2D binning procedure. S/N ~ 30.

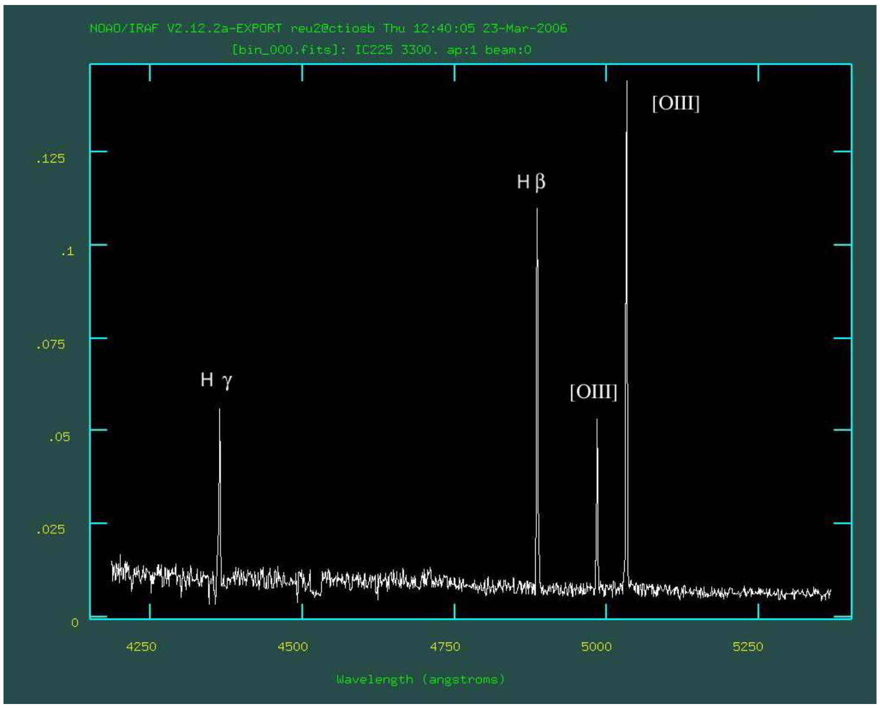

Fig. 6.— An example of the spectra following the reduction and rebinning procedure. The emission lines have been labled and are as follows: [OIII] $\lambda\lambda$4959, 5007, Hβ, Hγ.

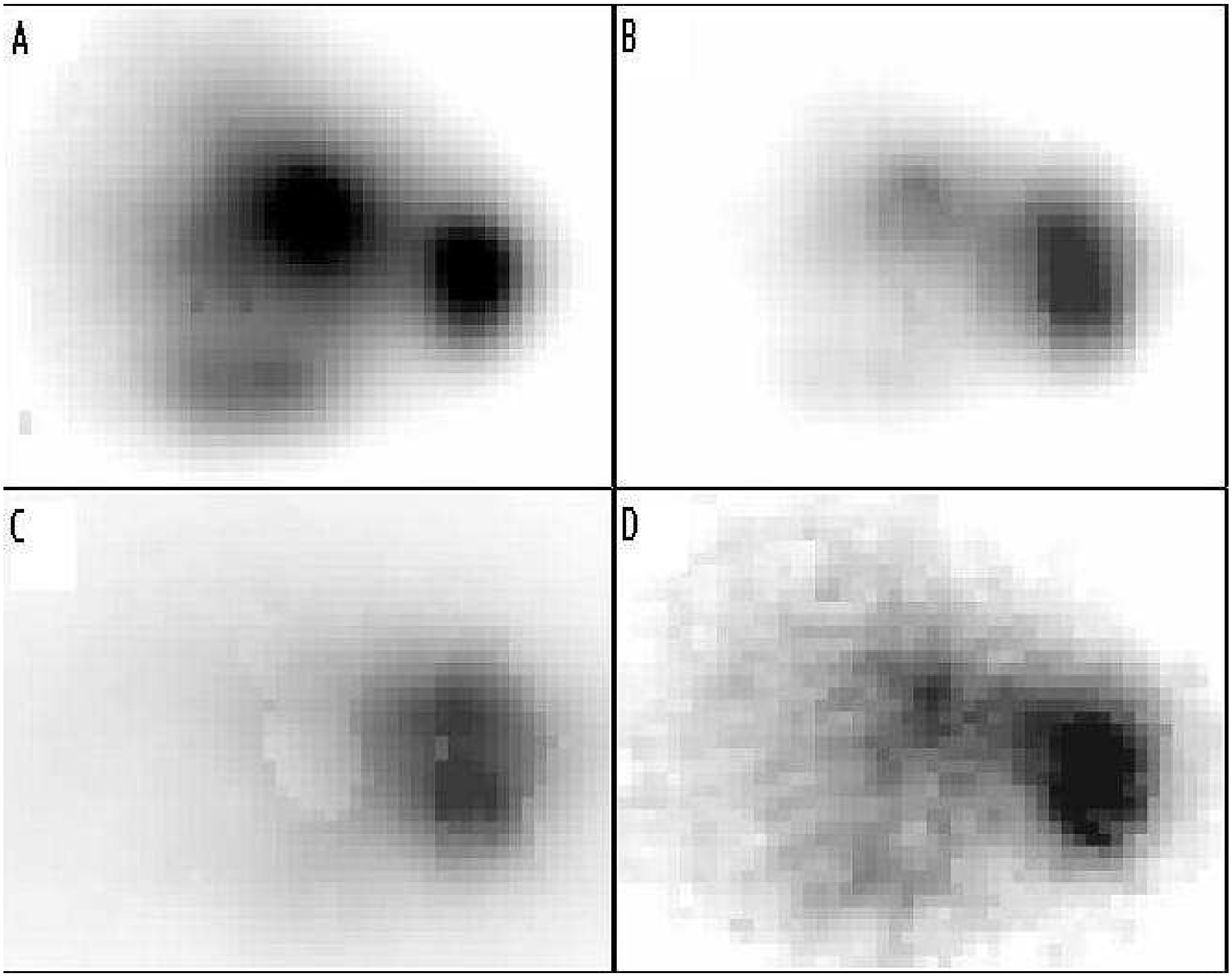

Fig. 7.— Four images of IC225. (A) Continuum section of the spectra compressed into a 2D field. The spectral range represented is 4370-4870 Å. (B) An [OIII] $\lambda\lambda$4959, 5007 image: the spectral range represented is 4980-5035 Å. (C) A Hβ image: the spectral range is 4883-4887 Å. (D) A Hγ image: the spectral range is 4360-4362 Å.

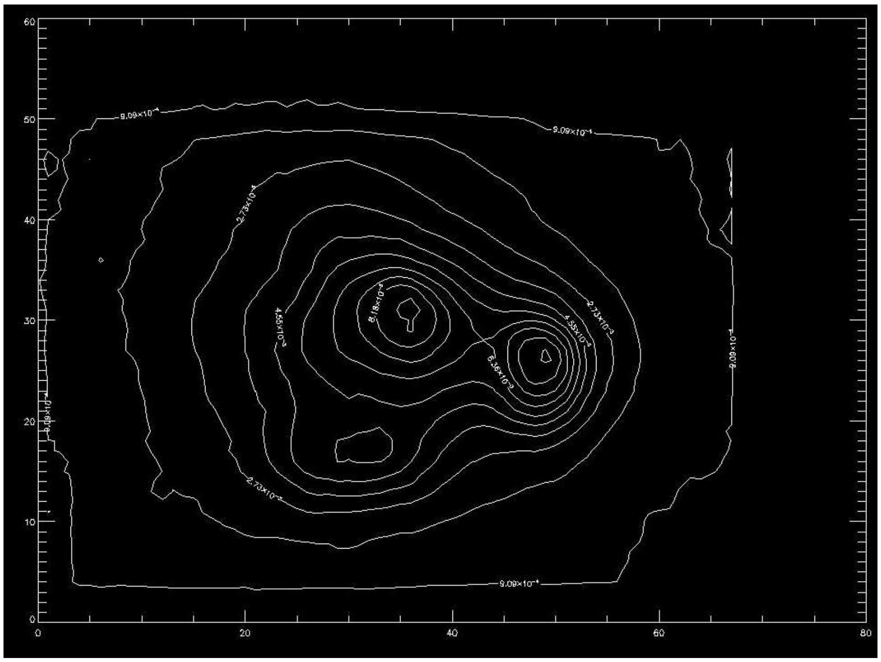

Fig. 8.— A contour image of IC225. Created with the continuum section of the spectra compressed into a 2D field. The spectral range represented is 4370-4870 Å.

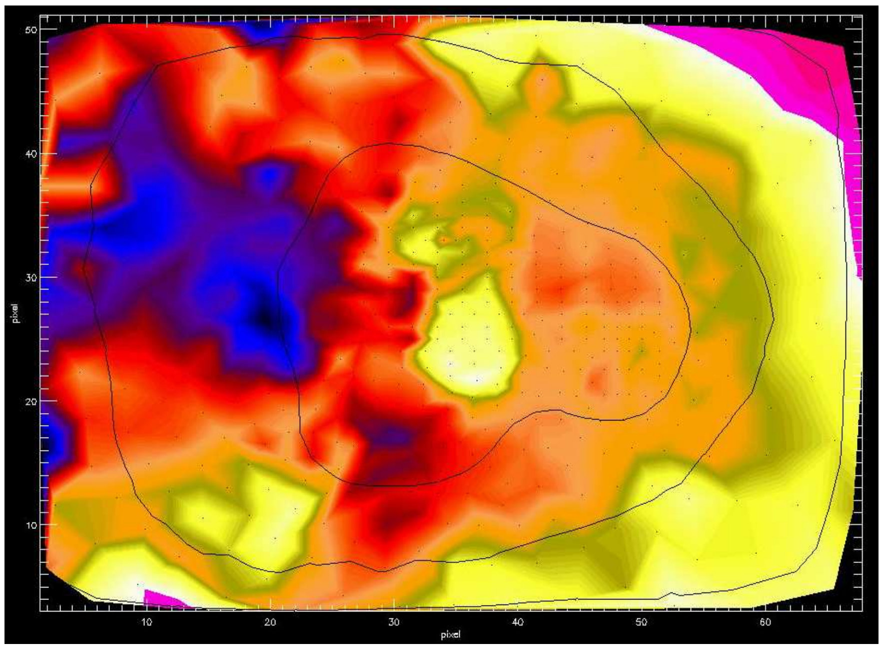

Fig. 9.— A relative velocity field of IC 225. This is based off the emission within the spectra which coorelates to the gas within the galaxy. Blue represents low values, red, medium values, and yellow is high values. The overplotted contour lines represent the isotropes of the continuum image.

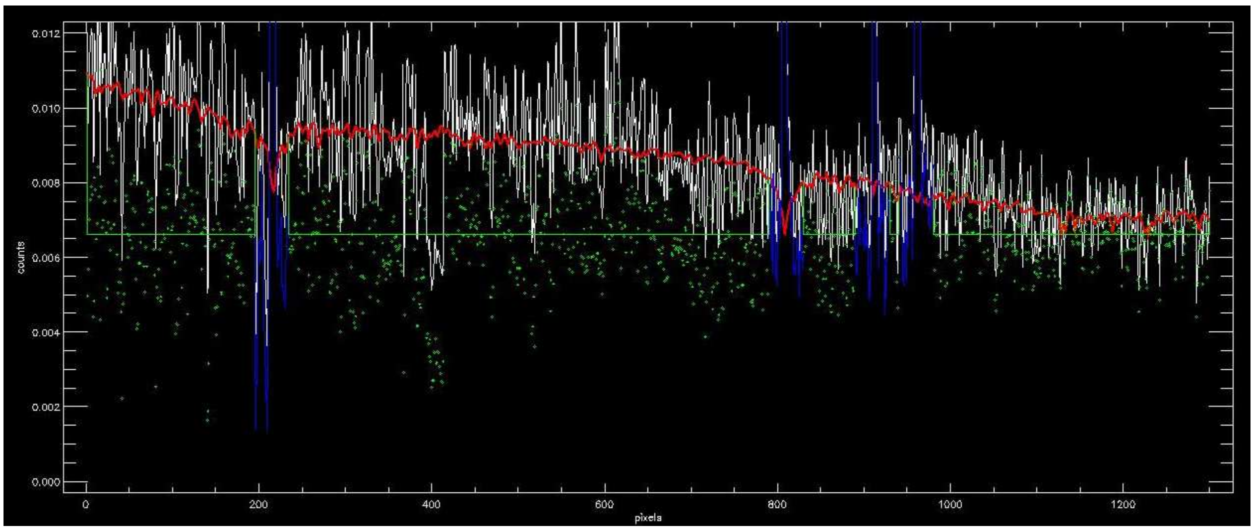

Fig. 10.— An example of the output from pPXF. The white line is the galaxy spectrum, the red line is the best fit stellar spectrum determined by the program, the blue curves represent the emission features subtracted from the fit, and the green points represent the residuals from the fit.

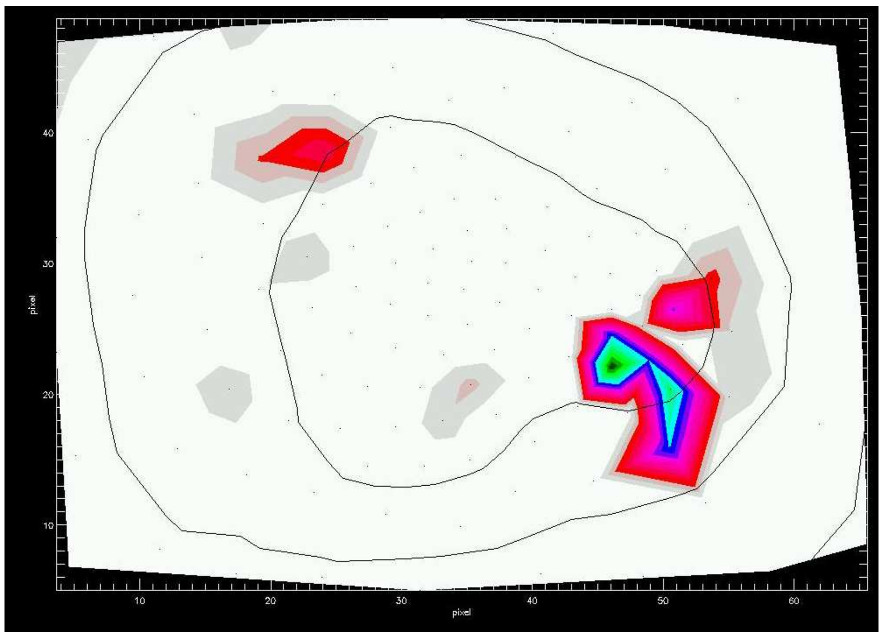

Fig. 11.— An absorbtion feature velocity field created using pPXF. White and Black represent the highest and lowest velocity values respectivly. Red represents high values and green meduium values. The field is overplotted with the isotropes of the continuum image of IC 225. Note the main motion is the field appears to be associated with the off-center nucleus.

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