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High Resolution Optical Spectra of HBC 722 after Outburst

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ABSTRACT

We report the results of our high resolution optical spectroscopic monitoring campaign (λ = 3800 – 8800 Å, R = 30000 – 45000) of the new FU Orionis-type object HBC 722. We observed HBC 722 with the BOES 1.8-m telescope between 2010 November 26 and 2010 December 29 and FU Orionis itself on 2011 January 26. We detect a number of previously unreported high-resolution K I and Ca II lines beyond 7500 Å. We resolve the Hα and Ca II line profiles into three velocity components, which we attribute to both disk and outflow. The increased accretion during outburst can heat the disk to produce the relatively narrow absorption feature and launch outflows appearing as high velocity blue and redshifted broad features.

Key words : keywords here — stars: formation – stars: FU Orionis – optical: spectroscopy – individual (HBC 722, FU Orionis)

1. INTRODUCTION

The standard star formation model predicted a constant accretion rate (Shu 1977; Tereby *et al.* 1984; Shu *et al.* 1987). However, recent studies based on surveys toward nearby low-mass star forming regions (Dunham *et al.* (2010) and references therein) suggest that the luminosities of young stellar objects are systematically low compared to the standard model. In addition, the discovery of Very Low Luminosity Objects (Young *et al.* 2004; Bourke *et al.* 2006, VeLLOs;) and their associated strong outflows (Andre *et al.* 1999; Lee *et al.* 2010) raised questions about the steady accretion process. As a result, an alternate mechanism, the episodic accretion process, has been suggested to account for these observational phenomena (Lee (2007) and references therein). The episodic accretion process is characterized by two phases: burst and quiescent accretion. FU Orionis-type objects (hereafter, FUors) have been proposed as prominent examples of burst accreting protostars while VeLLOs have been proposed as objects in the quiescent phase of the episodic accretion process.

FUors are a class of low-mass pre-main sequence objects named after FU Orionis, which produced a 5 magnitude optical outburst in 1936 and has remained in its brightened state. As a consequence of eruptive accretion these protostars exhibit large winds and outflows (Croswell, Hartmann, & Avrett 1987), which are inferred from P Cygni profiles of Hα and other lines. The spectral characteristics of FUors are broad blueshifted emission lines, IR excess, and near-IR CO overtone features, consequences of the energetic burst of accretion-driven viscous heating of the disk. Based on these characteristics, Hartmann & Kenyon (1996) and Reipurth & Aspin (2010) identified about dozen FUors, although in many cases the initial outburst had not been observed. Very little pre-outburst data exists for FUors; few have been studied from the pre-burst phase to the burst phase and only one (V1057 Cyg) has a pre-outburst optical spectrum.

HBC 722, also known as LkHα 188-G4 and PTF10qpf, was recently identified as an FUor by Semkov *et al.* (2010) and Miller *et al.* (2011). It brightened by ΔV=4.7 mag (Semkov *et al.* 2010), reaching its maximum brightness in September 2010, slowly decreasing since that time. HBC 722 (RA = 20h 58m 17.0s, Dec = +43° 53′ 42.9″, J2000) is in an active star forming region of North American/Pelican Nebula, 520 pc dis-

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tant (Laugalys *et al.* 2006). Pre-outburst, HBC 722 was identified as an emission line object of spectral type K7-M0 in the classical T Tauri phase with an interstellar reddening of $A_V = 3.4$ mag (Cohen & Kuhi 1979). During the burst, the optical and NIR spectra of HBC 722 became consistent with a G-type giant/supergiant and M-type giant/supergiant, respectively (Miller *et al.* 2011). The burst has not yet exhibited far-infrared feedback detectable with the instruments aboard the Herschel Space Observatory (Green *et al.* 2011). HBC 722 is the best-characterized FUor-like object pre-outburst and provides the first opportunity to profile the burst phase of accretion across all wavelengths, allowing us to model the process in detail.

Here we report the high resolution of optical spectra of HBC 722 observed about two months after reaching the maximum brightness of its outburst.

2. OBSERVATIONS

We have carried out optical high resolution spectroscopic observations of HBC 722 from 2010 November 26 to 2010 December 29 using the Bohyunsan Optical Echell Spectrograph (BOES, (Kim *et al.* 2002, 2007)) attached to the 1.8 m telescope in the Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. We also observed FU Orionis itself for comparison on 2011 January 26. All spectra were obtained with BOES using either the 200 (R $\sim$ 45,000) or 300 μm (R $\sim$ 30,000) fiber. The observed spectral regions cover the optical bands in 3800 Å − 8800 Å. The typical signal-to-noise ratio at 6700 Å is $\sim$ 15. The observation log is listed in Table 1.

The observed spectra were reduced with the IRAF `echelle` package to produce the spectra for each order of the echelle spectrum. The echelle aperture tracing was performed using the master flat image, a combination of all flat images. After aperture tracing, the flat, comparison, and object spectra were extracted from each image, with the same aperture reference as the master flat image. In the flatfielding process, the interference fringes and pixel-to-pixel variations of spectra were corrected. Wavelength calibration was performed with the ThAr lamp spectrum and the object spectra were normalized in each aperture using the `continuum` task.

3. ANALYSIS

First we identified lines from our BOES spectra of HBC 722 using the spectra presented in Miller *et al.* (2011) as a template. At wavelengths greater than 5000 A, the BOES spectra have relatively high S/N ratio, even to wavelengths greater than 8000 A. However lines located at wavelengths shorter than 5000 Å were difficult to identify because of the low S/N ratio in this region. The comparison of line identification between our spectra and those presented in Miller *et al.* (2011) is listed in Table 2. Figure 1 shows two K I lines near 7700 Å and Ca II triplet lines near 8500 Å. The spectra of FU Orionis are also plotted for comparison. Although these lines were detected in low resolution spectroscopy (Miller et al. 2011), the high resolution spectra presented here show clear blueshifted absorption and redshifted emission components; this P Cygni profile was previously reported only in Hα.

We selected two lines with strong P Cygni profiles, Hα and Ca II 8498, to perform a least-χ^2 fit with Gaussian profiles in order to examine the time-variations of central velocity, FWHM, and peak intensity for each component. The fitting results are shown in Figure 2 and Figure 3.

The Ca II 8498 lines can be decoupled into three components: a broad blue absorption feature, a broad red emission feature, and a relatively narrow central absorption feature. The broad blue absorption and red emission features are possibly associated with outflows while the relatively narrow absorption feature may be associated with the disk. If the narrow absorption profile is really produced by the disk, we can determine the radial velocity of HBC 722 as the central velocity of the profile, which has a small variation between -22 to -25 km s^{-1}. This idea is supported by the fact that the central velocities of two outflow components are apart about -50 km s^{-1} and +50 km s^{-1} from the central velocity of the narrow absorption profile, which is considered as the disk component.

The Hα lines are also decoupled into three velocity components as seen in Figure 3: a very broad but shallow blueshifted absorption feature, a relatively narrow blue absorption feature, and a very broad red emission feature. The very narrow emission feature superimposed on the broad emission feature is a telluric emission line (Hanuschik 2003), which was included in the fitting of the Gaussian profiles. The relatively narrow absorption feature might be associated with the disk component as suggested from the Ca II line. The central velocity of the very broad absorption feature is about -200 km s^{-1}, which is possibly the same fast outflow component as detected from the Hγ line in Miller *et al.* (2011). However, this very broad blue absorption feature was not detected on 23 December, probably due to very low S/N in this spectrum. The very broad blue absorption and red emission features must also be associated with outflows, indicative of different velocity components within the outflow. The broad red emission line is very bright compared to the blue absorption line; this large intensity difference possibly indicates that the outflow spans a large area.

In Figure 4, we plot the time variation of each parameter of these fitted Gaussian profiles in Hα and Ca II 8498 lines. The variation is not significant in most components given the low S/N ratio; the one exception to this is the FWHM of the broad red emission feature of Hα, which varied considerably during our observations. In addition, the peak intensity of the broad red

Table 1.
Observation Log

Target	Date	UT	Exposure time (sec)	Binning	Fiber (μm)	Spatial Resolution[a]	Seeing
HBC 722	2010 Nov 26	09:44	3600	2×2	300	4.3″	2.6″
HBC 722	2010 Dec 11	09:09	3600	1×1	300	4.3″	3.3″
HBC 722	2010 Dec 23	09:16	3600	2×2	200	2.9″	3.5″
HBC 722	2010 Dec 29	09:40	3600	2×2	200	2.9″	3.5″
FU Orionis[b]	2011 Jan 26	13:01	3600	1×1	200	2.9″	3.7″

[a] Spatial resolution corresponding to fiber size. This value means the fiber-tip field-of-view.
[b] The coordinates of FU Orionis are (RA; DEC)=(05h 45m 22.4s, +09° 04′ 12.4″, J2000).

emission feature seems correlated with the variation of its FWHM. The variation in the outflowing material is typically associated with a varying mass accretion rate (e.g. Kurosawa *et al.* (2006)). Therefore, in order to understand the accretion process post-outburst, we plan to monitor the variation of each velocity component when HBC 722 becomes observable again in April.

Table 2.
Detected Line List from High-resolution Spectra

Elem.	λ (Å)	This Work	Miller *et al.*
Fe II	5018.43	no	yes
Mg I	5167.32	no	yes
Fe II	5169.03	no	yes
Mg I	5172.63	yes	yes
Mg I	5183.60	yes	yes
Na I	5889.95	yes	yes
Na I	5895.92	yes	yes
Ba II	6141.71	no	yes
Ba II	6496.90	no	yes
Fe I	6393.60	no	yes
Fe I	6592.91	no	yes
Fe I	6677.99	no	yes
Hα	6562.79	yes	yes
K I	7664.90	yes	no
K I	7698.96	yes	no
Ca II	8498.02	yes	no
Ca II	8542.09	yes	no
Ca II	8662.14	yes	no

4. SUMMARY

We present a time series of BOES high resolution optical spectra of HBC 722, a newly reported FUor-like outburst during the summer of 2010. The high resolution spectra of two K I lines near 7700 Å and Ca II triplet lines near 8500 Å were covered uniquely by our observations. The P Cygni profiles were detected clearly in Hα and Ca II lines but only marginally in the K I lines. Using Gaussian profiles to fit the observed line profiles, we show that the Ca II 8498 and Hα 6563 lines trace the disk component as well as the outflow. The highest velocity component of the outflow (~ -200 km s^{-1}) was detected in the Hα line, and the broad red emission feature of the Hα line varies the most. Monitoring the variation of spectral features in the future will help our understanding of the kinematic structures and their time variations as HBC 722 returns to its pre-outburst state.

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REFERENCES

Andr, P., Motte, F., & Bacmann, A., 1999, Discovery of an Extremely Young Accreting Protostar in Taurus, ApJ, 513, L57

Bourke, T. L., Myers, P. C., Evans, N. J. II, Dunham, M. M., Kauffmann, J., et al., 2006, The Spitzer c2d Survey of Nearby Dense Cores. II. Discovery of a Low-Luminosity Object in the “Evolved Starless Core” L1521F, ApJ, 649, 37B

Cohen, M. H., & Kuhi, L. V., 1979, Observational studies of pre-main-sequence evolution, ApJS, 41, 743C

Dunham, M. M., Evans, N. J. II, Terebey, S., Dullemond, C. P., & Young, C. H., 2010, Evolutionary Signatures in the Formation of Low-Mass Protostars. II. Toward Reconciling Models and Observations, ApJ, 710, 470

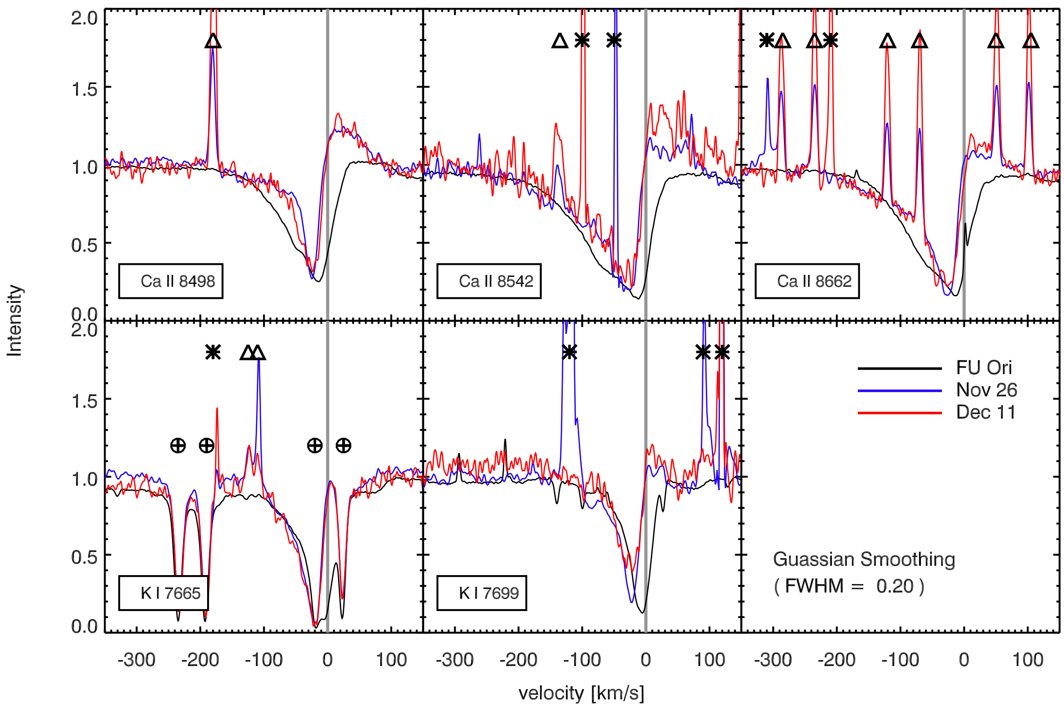

Fig. 1.— Ca II and K I lines observedin spectra taken on November 26 (blue) and December 11 (red), covered uniquely by our observations. All spectra are shown at the resolution smoothed to 0.2 Å. The spectrum of FU Orionis (black) is shown for comparison. Line intensity is normalized to the continuum level. Telluric emission lines (triangles; Hanuschik 2003), emission lines caused by hot pixels (asterisks), and telluric absorption (earth symbols) are marked.

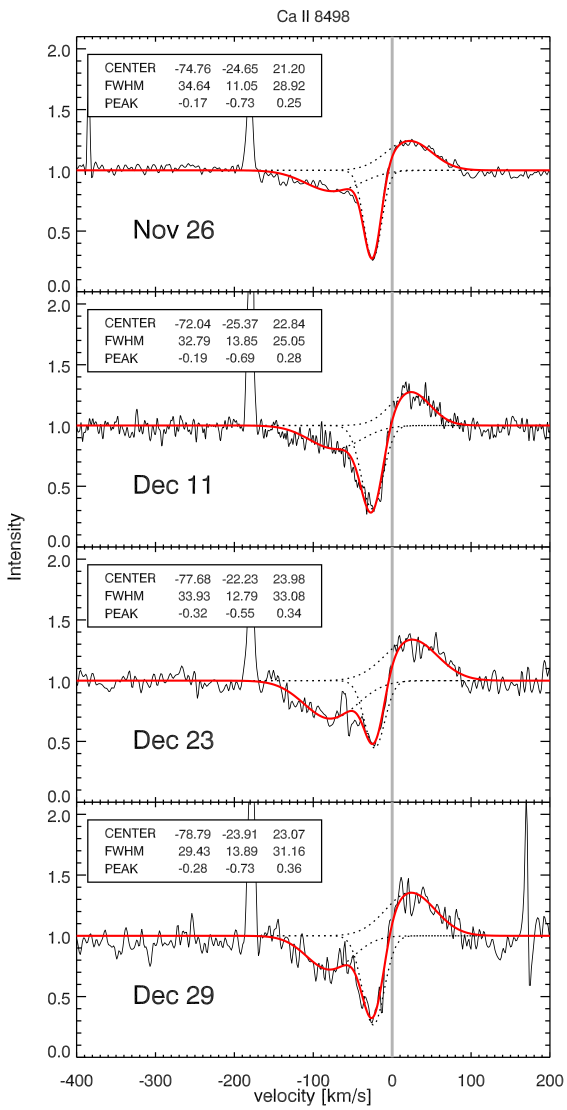

Fig. 2.— The Ca II 8498 spectra fitted with three Gaussian profiles: two absorption components at $v_{center} \sim -75$ and -25 km s^{-1} and an emission component around $v_{center} \sim +25$ km s^{-1}. The black dotted lines indicate fitted Gaussian profiles, and the red solid lines represent the whole combined profiles. Fit parameters including central velocity, peak intensity, and velocity FWHM are presented in legend boxes.

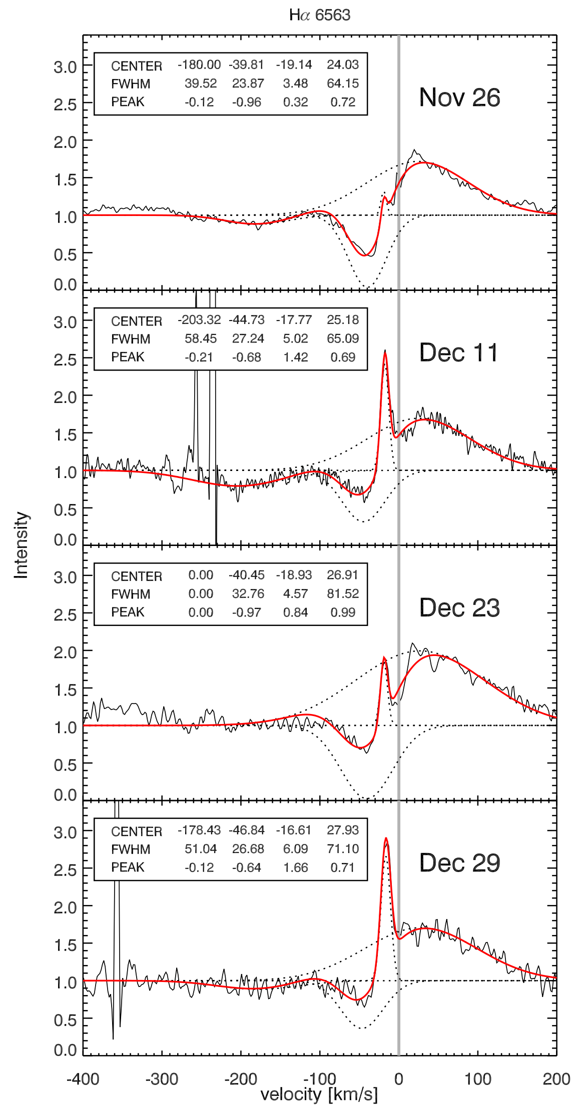

Fig. 3.— The Hα spectra fitted with four Gaussian profiles: two absorption components around $v_{center} \sim -200$ and -45 km s^{-1}, an emission component around $v_{center} \sim +25$km s^{-1}, and a telluric emission line. The line shapes and legends are all the same as in Figure 2.

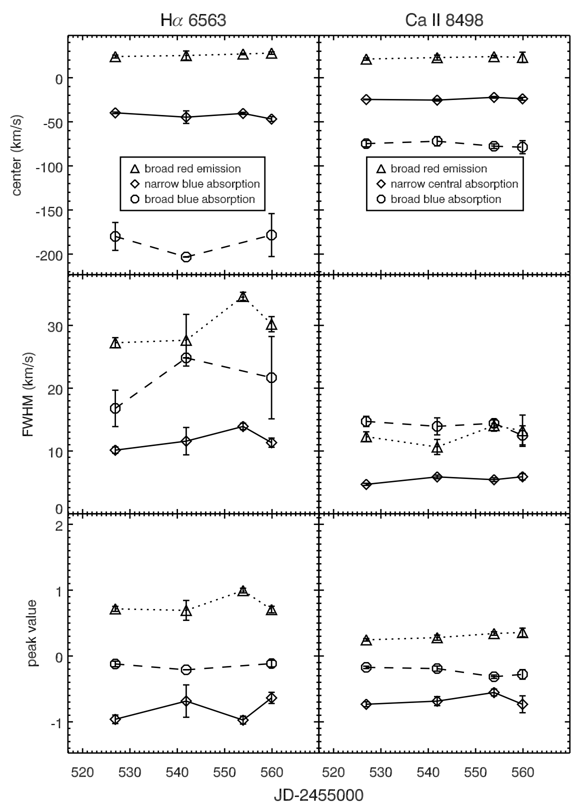

Fig. 4.— Time variation of each fitted parameter for the Hα and Ca II 8498 lines. Different symbols indicate the different velocity components of the lines (identified in legend boxes). Error bars represent formal 1σ errors.

Green, J. D., Evans, N. J. II, Kospal, A., Kempen, T. A., Herczeg, G., et al., 2011, Disentangling the Environment of the FU Orionis Candidate HBC 722 with Herschel, ApJL, 731, 25

Hanuschik, R. W., 2003, A flux-calibrated, high-resolution atlas of optical sky emission from UVES, A&A, 407, 1157

Hartmann, L., & Kenyon, S. J., 1996, The FU Orionis Phenomenon, ARA&A, 34, 1, 207

Kim, Kang-Min; Jang, Be-Ho; Han, Inwoo; Jang, Jeong Gyun, et al., 2002, Design and Manufacturing of the Cassegrain Interface Module of the BOAO Echelle Spectrograph, JKAS, 35, 221

Kim, K.-M., Han, I., Valyavin, G. G., Plachinda, S., et al., 2007, The BOES Spectropolarimeter for Zeeman Measurements of Stellar Magnetic Fields, PASP, 119, 1052

Kurosawa, R., Harries, T. J., Symington, Neil H., 2002, On the formation of H? line emission around classical T Tauri stars, MNRAS, 370, 580

Laugalys, V., Straizys, V., Vrba, F. J., Boyle, R. P., Davis Philip., A. G., et al., 2006, CCD Photometry and Classification of Stars in the North America and Pelican Nebulae Region. III. The Dark Cloud L935, BaltA, 15, 483L

Lee, J.-E., 2007, Chemical Evolution in VeLLOs, JKAS, 40, 85

Lee, J.-E. et al. 2010, The Spitzer c2d Survey of Nearby Dense Cores: Jet and Molecular Outflow Associated with a Young Stellar Object in Core A of L1251, ApJL, 709, 74

Miller, A. A., Hillenbrand, L. A., Covey, K. R., Poznanski, D., Silverman, J. M., 2011, Evidence for an FU Orionis-like Outburst from a Classical T Tauri Star, ApJ, 730, 80M

Reipurth, B., & Aspin, C., 2010, FUors and Early Stellar Evolution, vaoa.conf, 19R

Semkov, E., Peneva, S. P., Munari, U., Milani, A., Valisa, P., 2010 The large amplitude outburst of the young star HBC 722 in NGC 7000/IC 5070, a new FU Orionis candidate, A&A, 523L, 3S

Shu, F. H., 1977, Self-similar collapse of isothermal spheres and star formation, ApJ, 214, 488

Shu, F. H., Adams, F. C., & Lizano, S., 1987, Star formation in molecular clouds - Observation and theory, ARA&A, 25, 23

Terebey, S., Shu, F. H., & Cassen, P., 1984, The collapse of the cores of slowly rotating isothermal clouds, ApJ, 286, 529T

Young, C. H., Jorgensen, J. K., Shirley, Y. L., Kauffmann, J., Huard, T., et al., 2004, A "Starless" Core that Isn't: Detection of a Source in the L1014 Dense Core with the Spitzer Space Telescope, ApJS, 154, 396Y