THE ORION FINGERS: NEAR-IR SPECTRAL IMAGING OF AN EXPLOSIVE OUTFLOW

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ABSTRACT

We present near-IR (1.1–2.4 μm) position–position–velocity cubes of the 500 year old Orion BN/KL explosive outflow with spatial resolution 1″ and spectral resolution 86 km s⁻¹. We construct integrated intensity maps free of continuum sources of 15 H₂ and [Fe II] lines while preserving kinematic information of individual outflow features. Included in the detected H₂ lines are the 1-0 S(1) and 1-0 Q(3) transitions, allowing extinction measurements across the outflow. Additionally, we present dereddened flux ratios for over two dozen outflow features to allow for the characterization of the true excitation conditions of the BN/KL outflow. All of the ratios show the dominance of the shock excitation of the H₂ emission, although some features exhibit signs of fluorescent excitation from stellar radiation or J-type shocks. We also detect tracers of the PDR/ionization front north of the Trapezium stars in [O i] and [Fe II] and analyze other observed outflows not associated with the BN/KL outflow.

Key words: ISM: clouds – ISM: jets and outflows – stars: formation

1. INTRODUCTION

The Orion BN/KL outflow, located at 414 ± 7 pc (Menten et al. 2007), just behind the Orion Nebula, is an explosive, wide-angle outflow emerging from the OMC1 cloud core known for its bright, shock-excited H₂ and [Fe II] emission and several reflection nebulae. There is 8 ± 4 M☉ of material entrained in the inner, slow-moving (20 km s⁻¹) part of the outflow (Snell et al. 1984) with less than 1 M☉ in the high-velocity (150–300 km s⁻¹) fingers and bullets. Approximately 120 different jet-like structures are seen all with similar dynamic ages, indicating that they originate from a single event (Bally et al. 2015). In contrast to a group of traditional young stellar object (YSO) outflows, the velocity structure of the BN/KL outflow is consistent with a Hubble-type flow indicating an explosive origin (Zapata et al. 2009; Bally et al. 2015). Radio proper motion measurements show that the BN object, source I, and possibly source n were within 500 au from each other at (05:35:14.360, −05:22:28.70) approximately 500 years ago (Gomez et al. 2005; Rodriguez et al. 2005; Gomez et al. 2008; Goddi et al. 2011), and the near-IR bowshocks trace back to a common point within a few arcseconds of the ejection center (Bally et al. 2011, 2015). Possible launch mechanisms include the dynamical decay of an unstable multiple system of young stars (Zapata et al. 2009; Bally et al. 2015), a merger of massive stars (Bally & Zinnecker 2005), or a period of intense accretion onto source I caused by the close passage of a runaway massive star (Tan 2004; Chatterjee & Tan 2012).

All three proposed origins of the BN/KL outflow indicate this phenomenon might be common to massive star forming regions (SFRs), and other possible examples include DR21 (Zapata et al. 2013), G34.26+0.15 (Cyganowski et al. 2008), NGC 7129 (Eislöffel 2000; Gutermuth et al. 2004), IRAS 05506+2414 (Sahai et al. 2008), and W49 Source G (Smith et al. 2009). The BN/KL outflow is the closest and thus best for detailed observations diagnosing the conditions and properties of this type of outflow.

Observations of multiple transitions of H₂ can be used to derive excitation conditions of shocks on a pixel-by-pixel basis (e.g., Colgan et al. 2007). H₂ emission is excited collisionally with other H₂ molecules, H i, and electrons in hot 2000 K post-shock gas. These collisions populate only the lower vibrational levels in the ground electronic state, and Δν = 1 transitions resulting from quadrupolar radiative decay emit primarily in the K band (Wolff & Konigl 1991). However, UV photons from the Lyman and Werner bands can excite H₂ molecules to the first excited electronic state where the molecule can then dissociate (10% of the time) or decay into bound ro-vibrational levels of the electronic ground state resulting in a cascade of transitions down to the ground level (Black & Dalgarno 1976; Shull 1978; Black & van Dishoeck 1987). These two excitation mechanisms create distinct signatures in the flux ratios of the resulting K-band transitions. For example, a ~10:1 flux ratio in the 2.12 μm 1-0 S(1) to 2.24 μm 2-1 S(1) lines is expected for shocks (12 assuming LTE; Marconi et al. 1998) because only the lower vibrational levels are populated. UV-excited H₂ molecules can populate both high- and low-v states in the electronic ground state, decreasing the flux ratio in the 2.12 μm 1-0 S(1) to the 2.24 μm 2-1 S(1) line to ~2 (Black & Dalgarno 1976; Black & van Dishoeck 1987; Wolff & Konigl 1991).

We present medium-resolution, near-IR spectroscopy used to construct position–position–velocity (PPV) maps of the available H₂ and [Fe II] lines in the 1.1–2.4 μm range at ~1″ spatial resolution and 86 km s⁻¹ spectral resolution. Our constructed integrated intensity maps for the observed spectral lines exclude significant contamination by stars and reflection nebulosity and preserve kinematic information. We characterize the excitation conditions of the shocked gas and determine the kinematics of the wide-angle BN/KL outflow. In the optical, similar work has been presented by Doi et al. (2004), García-Díaz & Henney (2007), and García-Díaz et al. (2008) at higher spectral resolution and over a larger area of the Orion Nebula, but the optical only traces the foreground H II region.

Section 2 presents the observations and data reduction. Section 3 describes the results, including the H₂ and [Fe II] emission, kinematics, visual extinction, H₂ excitation, and YSO jets present in the field. Section 4 summarizes the results.

2. OBSERVATIONS AND REDUCTIONS

Spectra were obtained on 2012 November 5, 6, 24, and 25, and 2013 February 24 using the cross-dispersed near-IR
Integrated intensity maps of the emission lines were made using the pyspeckit Python module (Ginsburg & Mirocha 2011) which fits single Gaussians (background level, amplitude, $\sigma$, and velocity centroid as free parameters) to individual emission lines. The emission line flux was calculated analytically as the integral of a Gaussian ($\sqrt{2\pi} \sigma \Delta \lambda$). If the line was blended with an airglow line or had one or more within a few spectral-axis pixels, extra Gaussians were fit simultaneously and the original emission line flux was recovered. There are a few transitions of interest that completely coincide with airglow, and we were not able to recover the original emission flux. The free parameters of the Gaussian fit allow us to reconstruct mostly pure emission line maps with no stars or other continuum sources while retaining kinematic information from the velocity centroid and sigma. The exception is three bright stars (BN object, V2248 Ori, and MT Ori) erroneously contribute emission in some of our integrated intensity maps. They have been marked in many of the figures for easy identification of stellar contamination.

Fits were made only for lines above a signal-to-noise ratio (S/N) threshold of 10. Linewidths ($\sigma$) were constrained between 1 and 5 Å. To replace missing pixels where no fits occurred, we used 2D interpolation over the integrated intensity maps. Uncertainties in the fluxes are typically no more than 30%.

Absolute flux calibration with long-slit spectroscopy is not possible because an unknown fraction of the standard star’s light falls outside the slit. To account for this missing flux, we made $H_2$ 1-0 S(1) 2.12 μm integrated intensity maps from each of our individual slit scans and compared them to a 2010 APO NICFPS $H_2$ 1-0 S(1) flux-calibrated image. We used the ratio of the two images to increase the flux appropriately in each of the data cubes before averaging them together. The typical correction factor ranged from 1.4 to 3.4 with an average of 2.

3. RESULTS

The PPV cubes presented here provide the first wide-field near-IR view of the Orion BN/KL outflow in dozens of spectral lines. We utilize integrated intensity maps of $H_2$ and [Fe II] to diagnose the kinematics and excitation conditions of the region.

3.1. $H_2$ Fingers

The famous $H_2$ fingers of the BN/KL outflow are visible and unaffected by significant telluric absorption in 22 ro-vibrational $H_2$ lines in our TripleSpec spectra. However, approximately half of these transitions are coincident with telluric emission (airglow), making them only useful for determining the morphology of the emission in that line. Figures 1 and 2 show $H_2$ v = 1 → 0 S branch ($\Delta J = +2$) and $v = 1 → 0 Q$ branch ($\Delta J = 0$) integrated intensity maps free of continuum sources. The positions of the BN object, source I, and source n are denoted in each figure by a blue square, magenta triangle, and green X, respectively. The BN object, V2248 Ori (05:35:13.8, −5:21:59.6) and MT Ori (05:35:17.9, −5:22:45.4) sometimes contaminate the pure emission line maps (see Section 2). The quality of the maps depends jointly on the S/N of the line and airglow contamination. Many of the lines suffer from at least partial contamination (within a few pixels of the line core), and

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3 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4 The J-, H-, and K-band PPV cubes are available for download at http://dx.doi.org/10.7910/DVN/YUNZ1F. The reduction scripts are available at https://github.com/allisony/TspecCubes.

5 By default pyspeckit uses the Levenberg–Marquardt algorithm via MPFIT (Markwardt 2009).
the higher S/N lines allow for easier simultaneous fitting of the source line and airglow contaminant.

The greatest H$_2$ intensity occurs in the central 85" × 75" region—Peak 1 and Peak 2 (Beckwith et al. 1978)—where the proper motion of the outflow is the slowest (Bally et al. 2015). The fingers with the greatest proper motions (150–300 km s$^{-1}$) extend 1.5–2.5 away from the center of the outflow. Figure 5 shows the intensity-weighted radial velocities ($v_{LSR}$) and linewidths of the H$_2$ 1-0 S(1) line derived from the pyspeckit fits. The central region of the flow is generally blueshifted and exhibits broader linewidths, while the outer fingers are typically redshifted (see Section 3.1.3). The fast-moving fingers are primarily in the plane of the sky because the proper motions are more than twice the line of sight motion, while the slow-moving fingers are not.

### 3.1.1. Visual Extinction

To recover the intrinsic emission from the observed H$_2$ line emission and derive the true excitation pixel-by-pixel, we constructed a visual extinction ($A_V$) map from the H$_2$ 1-0 Q(3)
and 1-0 S(1) lines. These two lines originate from the same upper state ($v = 1, J = 3$) and have an intrinsic line ratio of 0.74 (Geballe et al. 1982). We assumed a typical near-IR extinction law from Cardelli et al. (1989) to derive $A_V$ (Figure 3). $H_2$ 1-0 Q(3) is partially blended with at least one airglow line, and as a result, the individual slit scans with severe airglow contamination were excluded from the $A_V$ map. $A_V$ is as low as 3.5 mag in the southeastern part of the outflow, and as high as 35 mag in the northern fingers. In the central regions, the extinction is typically 20 mag. Regions with low S/N typically over-predict $A_V$ because airglow contamination dominates the 1-0 Q(3) line there. Assuming a typical gas-to-dust ratio of 100, the $H_1 + H_2$ column density in the central region is $\sim 4 \times 10^{22}$ cm$^{-2}$, consistent with the $H_2$ emission originating inside the OMC1 cloud.

Figure 3 also shows the visual extinction as a function of position angle (PA). The center is the origin of the outflow (05:35:14.360, -05:22:28.70) and PA = 0° and 270° are north and east, respectively. Each point represents a single pixel in the $A_V$ map in the left panel of Figure 3. Along the outflow axis
The locations of the BN object, source I, and source n, respectively. The red squares mark the locations of V2248 Ori indicating shocks are the dominant excitation mechanism of the Orion A integral-shaped filament (Salji et al. 2015), so we do not expect low extinction values.

3.1.2. Shock Excitation

Figure 4 shows the ratio between the 1-0 S(1) and 2-1 S(1) lines, a common shock diagnostic, before extinction correction and after. In the extinction-corrected ratio map, the pixels with ratios $<10$ indicate some UV excitation, although it is not dominant. Goicoechea et al. (2015b) and Chen et al. (2014) confirm the far-UV irradiation of the shocked material in the BN/KL outflow but cannot distinguish between an external source like the Trapezium or internal illumination by J-type shocks. The observed flux ratios of various knots highlighted in Figure 6 and Table 1 are presented in Table 2, and Table 3 presents the de-reddened flux ratios for the same knots. For the selected knots, the 1-0 S(1)/2-1 S(1) ratio varies from 6 to 12.5, indicating shocks are the dominant excitation mechanism of the H$_2$ molecules.

3.1.3. Kinematics

The radial velocity map shows that the central region of the BN/KL outflow is generally blueshifted and the outer fingers are generally redshifted (Figure 5). However, CO observations of the central region of the outflow show roughly the same number of redshifted and blueshifted streamers (Zapata et al. 2009), indicating the outflow may be isotropic. The receding H$_2$ fingers in the central region are probably hidden by dense gas ($A_V \approx 20$ mag) from the OMC1 hot core. The H$_2$ linewidths in the central region are large (FWHM $\approx 115-140$ km s$^{-1}$, deconvolved FWHM $\approx 76-110$ km s$^{-1}$), and the expected radial velocity differences of the blueshifted and redshifted flows are of the order of TripleSpec's 86 km s$^{-1}$ spectral resolution. It is possible that blueshifted and redshifted H$_2$ fingers coincident on the plane-of-the-sky are simply not spectrally resolved. This is especially likely if the redshifted fingers are much fainter than the blueshifted fingers because our single Gaussian fits' velocity centroids will be skewed to the brighter velocity components. The redshifted fingers, as mentioned above, are likely to suffer from more extinction than the blueshifted fingers. Also, the CO observations (Zapata et al. 2009) generally show radial velocities $v_{LSR} < -30$ km s$^{-1}$ and $v_{LSR} > +30$ km s$^{-1}$, but our H$_2$ radial velocities are $-30$ km s$^{-1} < v_{LSR} < +30$ km s$^{-1}$. This indicates the near-IR H$_2$ shocks may not be tracing the same gas as seen in CO.

The radial velocity and linewidth (FWHM) maps (Figure 5; calculated from the single Gaussian fits' $\lambda_0$ and $\sigma$ parameters) combined with the $A_V$ map (Figure 3) reveal kinematically...
Table 1

Coordinates for Labeled H₂ Features in Figure 6

| Number | R.A. (J2000) | decl. (J2000) | \(v_{LSR}\)^a (km s\(^{-1}\)) |
|--------|-------------|--------------|-----------------|
| 1      | 5:35:14.816 | −5:20:36.99  | 20 ± 5          |
| 2      | 5:35:14.004 | −5:20:30.57  | 9 ± 12          |
| 3      | 5:35:13.051 | −5:20:39.44  | 10 ± 4          |
| 4      | 5:35:12.209 | −5:20:39.76  | −2 ± 28         |
| 5      | 5:35:15.721 | −5:21:13.3   | 10 ± 5          |
| 6      | 5:35:13.369 | −5:20:55.88  | 7 ± 5           |
| 7      | 5:35:11.597 | −5:20:54.32  | −19 ± 27        |
| 8      | 5:35:11.864 | −5:21:17.11  | 4 ± 4           |
| 9      | 5:35:10.548 | −5:21:28.19  | 11 ± 6          |
| 10     | 5:35:12.002 | −5:21:42.85  | 2 ± 7           |
| 11     | 5:35:13.72  | −5:21:52.94  | 1 ± 8           |
| 12     | 5:35:14.739 | −5:21:56.83  | 4 ± 5           |
| 13     | 5:35:16.845 | −5:22:8.69   | 4 ± 4           |
| 14     | 5:35:14.963 | −5:22:21.62  | 1 ± 5           |
| 15     | 5:35:11.313 | −5:22:19.14  | 11 ± 4          |
| 16     | 5:35:14.645 | −5:22:32.61  | −15 ± 8         |
| 17     | 5:35:14.068 | −5:22:37.82  | −8 ± 8          |
| 18     | 5:35:13.703 | −5:22:39.2   | −11 ± 6         |
| 19     | 5:35:12.818 | −5:22:47.94  | 7 ± 1           |
| 20     | 5:35:11.849 | −5:22:38.98  | 12 ± 3          |
| 21     | 5:35:15.345 | −5:22:37.18  | 19 ± 4          |
| 22     | 5:35:17.947 | −5:23:6.31   | 2 ± 2           |
| 23     | 5:35:18.795 | −5:23:9.79   | 8 ± 2           |
| 24     | 5:35:19.367 | −5:23:12.02  | 7 ± 4           |
| 25     | 5:35:13.109 | −5:22:3.84   | 8 ± 8           |
| 26     | 5:35:13.576 | −5:22:3.57   | 1 ± 8           |
| 27     | 5:35:13.205 | −5:22:21.79  | −4 ± 10         |

Note.

\(^a\)H₂ intensity-weighted radial velocities measured as the median value of the measurements for the transitions reported in Table 2. The uncertainty is reported in this table is the standard deviation of the measurements.

distinct outflow features that would not be apparent from the integrated intensity maps alone. Figure 6 and Table 1 highlight specific outflows with unique properties. Feature #14 (see Figure 6 for numbered features) with the largest linewidth of 150 km s\(^{-1}\) (deconvolved FWHM = 122 km s\(^{-1}\)) is a blueshifted \(v_{LSR} = −8\) km s\(^{-1}\) knot located at (05:35:14.961, −5:22:21.87). With a H₂ 1-0 S(1) total flux of 7.25 × 10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), it is among the dimmer knots. At (05:35:15.348, −5:22:37.48) lies the significantly redshifted (\(v_{LSR} = +30\) km s\(^{-1}\)) knot #21 that also stands out kinematically because it is slightly broader than its surroundings. Like the previous knot, it is almost indistinguishable from its surroundings in H₂ intensity.

Knot #21’s \(A_V \sim 10\) mag, is distinctly smaller than the surrounding area’s \(A_V \sim 20–25\) mag, suggesting that this knot is either on the far side of the flow and is only visible through a cavity or is an unrelated foreground flow. The area to the east of knot #21 also shows \(A_V\) lower than its surroundings, and the shape of the low \(A_V\) values corresponds to an H₂ finger #21-E at (5:35:16.881, −5:22:36.01) seen at \(v_{LSR} = +20\) km s\(^{-1}\) redshift. \(A_V\) is also relatively small for the H₂ fingers in the southeast and the west. Knots of anomalous velocity with respect to the surrounding H₂ flow typically correspond to regions of low extinction, such as the knot #2-S on the northern-most finger at (5:35:14.164, −5:20:39.24). #2-S also corresponds to an [Fe \(\Pi\)] bullet. Near the center of the outflow lies an x-shaped feature #26-SE (5:35:14, −5:22:13:72) of low extinction that corresponds to a redshifted feature.

As mentioned in Section 2, the discrete fit to the standard star trace introduced a velocity gradient into the PPV cube in the direction of the slit scans. This effect can be seen in Figure 5 where many of the H₂ fingers show blueshifted emission to the north, and redshifted emission to the south. Other fingers where this effect is not seen have data coverage from two slit scans in
| No. | 1-0 S(1)$^b$ | 1-0 S(0)$^c$ | 1-0 S(7) | 1-0 S(8) | 1-0 S(9) | 2-1 S(0) | 2-1 S(1) | 3-2 S(3) | 3-2 S(5) | 1-0 Q(1) | 1-0 Q(2) | 1-0 Q(3) | 1-0 Q(4) |
|-----|--------------|--------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1   | 6.20 $\times$ 10^{-13} | 0.27 | 0.18 | ... | ... | ... | 0.09 | ... | ... | 1.48 | ... | ... | 0.99 | ... |
| 2   | 5.31 $\times$ 10^{-14} | ... | 0.32 | ... | 0.14 | ... | ... | ... | ... | 1.53 | ... | ... | 1.26 | ... |
| 3   | 7.71 $\times$ 10^{-14} | ... | ... | ... | ... | ... | 0.15 | ... | ... | 1.55 | ... | ... | 1.26 | 0.43 |
| 4   | 5.71 $\times$ 10^{-14} | 0.27 | 0.29 | ... | ... | ... | ... | ... | ... | 2.05 | ... | ... | 1.56 | ... |
| 5   | 3.33 $\times$ 10^{-14} | ... | 0.15 | ... | ... | ... | ... | ... | ... | 1.38 | ... | ... | 1.18 | ... |
| 6   | 2.05 $\times$ 10^{-14} | 0.26 | 0.25 | ... | ... | ... | 0.12 | ... | ... | 1.56 | ... | ... | 1.24 | 0.36 |
| 7   | 7.77 $\times$ 10^{-14} | 0.26 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 8   | 1.02 $\times$ 10^{-13} | ... | 0.25 | ... | ... | ... | 0.12 | ... | ... | 1.29 | ... | ... | 1.0 | ... |
| 9   | 5.28 $\times$ 10^{-14} | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1.26 | ... |
| 10  | 9.16 $\times$ 10^{-14} | 0.26 | 0.17 | ... | 0.04 | ... | 0.09 | ... | ... | 1.26 | 0.36 | 1.03 | 0.22 | ... |
| 11  | 4.59 $\times$ 10^{-13} | 0.27 | 0.14 | 0.02 | 0.03 | 0.03 | 0.11 | 0.02 | 0.01 | 1.25 | 0.37 | 1.11 | 0.31 | ... |
| 12  | 1.22 $\times$ 10^{-13} | 0.29 | 0.1 | ... | 0.03 | 0.11 | 0.02 | ... | ... | 1.52 | 0.41 | 1.28 | 0.33 | ... |
| 13  | 1.93 $\times$ 10^{-14} | 0.29 | ... | ... | ... | ... | 0.13 | ... | ... | 2.04 | ... | 1.41 | ... | ... |
| 14  | 7.27 $\times$ 10^{-14} | 0.28 | 0.12 | ... | ... | ... | 0.1 | ... | ... | 1.5 | ... | 1.18 | 0.2 | ... |
| 15  | 1.39 $\times$ 10^{-13} | 0.27 | 0.17 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 16  | 1.81 $\times$ 10^{-13} | 0.28 | 0.13 | ... | 0.02 | 0.03 | 0.09 | 0.02 | ... | 1.29 | 0.36 | 1.14 | 0.32 | ... |
| 17  | 2.56 $\times$ 10^{-13} | 0.28 | 0.13 | ... | 0.02 | ... | 0.08 | 0.02 | ... | 1.35 | 0.36 | 1.14 | 0.3 | ... |
| 18  | 9.33 $\times$ 10^{-14} | 0.28 | 0.11 | ... | 0.02 | 0.03 | 0.09 | 0.01 | ... | 1.34 | 0.39 | 1.25 | 0.33 | ... |
| 19  | 2.43 $\times$ 10^{-13} | 0.3 | 0.09 | ... | ... | ... | 0.11 | ... | ... | 1.72 | ... | 1.47 | 0.36 | ... |
| 20  | 1.07 $\times$ 10^{-13} | 0.27 | 0.14 | ... | ... | ... | 0.11 | ... | ... | 1.07 | ... | 0.96 | 0.27 | ... |
| 21  | 2.26 $\times$ 10^{-13} | 0.28 | 0.1 | ... | ... | ... | 0.09 | ... | ... | 1.2 | 0.43 | 0.95 | 0.3 | ... |
| 22  | 5.11 $\times$ 10^{-14} | 0.29 | 0.21 | ... | ... | ... | 0.12 | ... | ... | ... | ... | ... | ... | ... |
| 23  | 1.51 $\times$ 10^{-14} | 0.3 | 0.17 | ... | ... | ... | 0.14 | ... | ... | ... | ... | ... | 0.8 | ... |
| 24  | 3.85 $\times$ 10^{-14} | 0.28 | 0.2 | ... | ... | ... | 0.15 | ... | ... | ... | ... | ... | 0.81 | ... |
| 25  | 3.69 $\times$ 10^{-13} | 0.3 | 0.14 | 0.02 | 0.03 | 0.03 | 0.11 | 0.02 | 0.01 | 1.34 | 0.39 | 1.13 | 0.33 | ... |
| 26  | 5.74 $\times$ 10^{-13} | 0.28 | 0.13 | 0.02 | 0.03 | 0.03 | 0.1 | 0.02 | 0.01 | 1.28 | 0.37 | 1.09 | 0.33 | ... |
| 27  | 3.23 $\times$ 10^{-13} | 0.27 | 0.13 | 0.02 | 0.03 | ... | 0.09 | 0.02 | ... | 1.17 | 0.36 | 1.04 | 0.31 | ... |
| 28  | 1.28 $\times$ 10^{-13} | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 29  | 2.51 $\times$ 10^{-13} | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 30  | 3.79 $\times$ 10^{-13} | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

Notes:

$^a$ erg s$^{-1}$ cm$^{-2}$

$^b$ Fluxes are estimated to have ±30% accuracy (Section 2). Propagating this uncertainty estimates the flux ratios to have ±42% accuracy.

$^c$ All other transition fluxes normalized to 1-0 S(1) value.
Table 3

Derreddened H$_2$ Fluxes for Features Labeled in Figure 6

| No. | 1-0 S(1)$^a$ | 1-0 S(0)$^b$ | 1-0 S(7) | 1-0 S(8) | 2-1 S(0) | 2-1 S(1) | 3-2 S(3) | 3-2 S(5) | 1-0 Q(1) | 1-0 Q(2) | 1-0 Q(3)$^b$ | 1-0 Q(4) |
|-----|--------------|--------------|----------|----------|----------|----------|----------|----------|----------|----------|-------------|----------|
| 1   | 2.42 × 10$^{-14}$ | 0.24         | 0.32     | ...      | ...      | 0.08     | ...      | ...      | 1.12     | ...      | 0.74         | ...      |
| 2   | 6.88 × 10$^{-13}$ | ...          | 0.97     | ...      | ...      | 0.54     | ...      | ...      | ...      | ...      | 0.74         | ...      |
| 3   | 7.42 × 10$^{-13}$ | ...          | ...      | ...      | ...      | ...      | ...      | 0.99     | ...      | ...      | 0.74         | ...      |
| 4   | 7.50 × 10$^{-13}$ | 0.22         | 0.86     | ...      | ...      | ...      | 0.12     | ...      | 0.94     | ...      | 0.74         | 0.25     |
| 5   | 1.17 × 10$^{-12}$ | ...          | 0.71     | ...      | ...      | ...      | ...      | 1.01     | ...      | ...      | 0.74         | ...      |
| 6   | 1.90 × 10$^{-13}$ | 0.22         | 0.65     | ...      | ...      | ...      | 0.1      | ...      | 0.9      | ...      | 0.74         | ...      |
| 7   | 3.29 × 10$^{-13}$ | 0.21         | ...      | ...      | ...      | ...      | ...      | 0.95     | ...      | ...      | 0.74         | 0.22     |
| 8   | 4.69 × 10$^{-13}$ | ...          | 0.54     | ...      | ...      | ...      | 0.11     | ...      | 0.99     | ...      | 0.74         | ...      |
| 9   | 6.87 × 10$^{-13}$ | ...          | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | 0.74         | ...      |
| 10  | 4.45 × 10$^{-13}$ | 0.23         | 0.33     | ...      | 0.09     | ...      | 0.08     | ...      | 0.92     | 0.26     | 0.74         | 0.15     |
| 11  | 3.09 × 10$^{-12}$ | 0.23         | 0.3      | 0.05     | 0.08     | 0.02     | 0.09     | 0.02     | 0.01     | 0.85     | 0.25         | 0.74     |
| 12  | 1.66 × 10$^{-12}$ | 0.23         | 0.29     | ...      | ...      | 0.02     | 0.08     | 0.02     | ...      | 0.9      | 0.24         | 0.74     |
| 13  | 4.08 × 10$^{-13}$ | 0.23         | ...      | ...      | ...      | ...      | 0.1      | ...      | ...      | 1.11     | ...          | 0.74     |
| 14  | 6.55 × 10$^{-13}$ | 0.24         | 0.3      | ...      | ...      | ...      | 0.08     | ...      | ...      | 0.97     | ...          | 0.74     |
| 15  | ...            | ...          | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...          | ...      |
| 16  | 1.38 × 10$^{-12}$ | 0.24         | 0.3      | ...      | 0.06     | 0.02     | 0.07     | 0.02     | ...      | 0.85     | 0.24         | 0.74     |
| 17  | 1.98 × 10$^{-12}$ | 0.23         | 0.3      | ...      | 0.06     | ...      | 0.07     | 0.01     | ...      | 0.89     | 0.24         | 0.74     |
| 18  | 1.09 × 10$^{-12}$ | 0.23         | 0.31     | ...      | 0.08     | 0.02     | 0.07     | 0.01     | ...      | 0.81     | 0.24         | 0.74     |
| 19  | 1.57 × 10$^{-11}$ | 0.32         | 2.06     | ...      | ...      | ...      | 0.11     | ...      | ...      | 0.9      | ...          | 0.74     |
| 20  | 3.63 × 10$^{-13}$ | 0.21         | 0.25     | ...      | ...      | ...      | 0.1      | ...      | ...      | 0.84     | ...          | 0.74     |
| 21  | 7.41 × 10$^{-13}$ | 0.26         | 0.17     | ...      | ...      | ...      | 0.08     | ...      | 0.96     | 0.33     | 0.74         | 0.23     |
| 22  | ...            | ...          | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...          | ...      |
| 23  | 2.27 × 10$^{-14}$ | 0.29         | 0.21     | ...      | ...      | ...      | 0.13     | ...      | ...      | ...      | 0.74         | ...      |
| 24  | 6.33 × 10$^{-14}$ | 0.28         | 0.28     | ...      | ...      | ...      | 0.15     | ...      | ...      | ...      | 0.74         | ...      |
| 25  | 7.69 × 10$^{-12}$ | 0.35         | 2.07     | 0.35     | 0.67     | 0.02     | 0.12     | 0.03     | 0.03     | 0.9      | 0.26         | 0.74     |
| 26  | 5.10 × 10$^{-12}$ | 0.29         | 1.08     | 0.18     | 0.34     | 0.02     | 0.1      | 0.02     | 0.02     | 0.89     | 0.25         | 0.74     |
| 27  | 1.64 × 10$^{-12}$ | 0.24         | 0.25     | 0.04     | 0.06     | ...      | 0.08     | 0.02     | ...      | 0.85     | 0.26         | 0.74     |
| 28  | 1.65 × 10$^{-10}$ | ...          | ...      | ...      | ...      | ...      | ...      | ...      | ...      | ...      | 0.74         | ...      |
| 29  | 3.72 × 10$^{-10}$ | ...          | ...      | ...      | ...      | ...      | 0.3      | ...      | ...      | ...      | 0.74         | ...      |
| 30  | 5.37 × 10$^{-10}$ | ...          | ...      | ...      | ...      | ...      | 0.23     | ...      | ...      | ...      | 0.74         | ...      |

Notes.

$^a$ erg s$^{-1}$ cm$^{-2}$

$^b$ All other transition fluxes normalized to 1-0 S(1) value.

$^c$ Dereddening was performed using the 1-0 Q(3)/1-0 S(1) = 0.74 intrinsic flux ratio (Section 3.1.1; Geballe et al. 1982).
orthogonal directions. No region of the cube has only east-west slit scan coverage, hence when the velocity gradient is seen, it is only in the north–south direction.

3.2. \textit{[Fe II] Fingertips}

We detect bright \textit{[Fe II]} emission lines at 1.26 and 1.64 \textit{\mu}m and their related transitions originating from the $4D$ term (second excited state) and terminating in the $6D$ (ground state) and $4F$ (first excited state) terms, respectively. The \textit{[Fe II]} emission is seen only around the shock heads (the fingertips) as the $4D$ term requires 12,000 K collisional excitation (Smith & Hartigan 2006). Also, \textit{[Fe II]} emission is likely enhanced when grain sputtering via shocks or shock-heating creates a partially ionized zone, thus increasing the gas phase abundance of iron (Greenhouse et al. 1991; Mouri & Taniguchi 2000). The fingertip \textit{[Fe II]} emission appears primarily in the outer, faster-moving fingers in the plane of the sky, although there are a few \textit{[Fe II]} knots visible in the central, blueshifted part of the flow (Figure 7).

The 1.26 and 1.64 \textit{\mu}m transitions can be used to measure extinction because they both originate from the same upper
level \((^4D)\) and have an intrinsic flux ratio 
\(F(\lambda 12567)/F(\lambda 16435) = 1.49\) (Smith & Hartigan 2006), however, the 1.64 \(\mu\)m line is coincident with an airglow line and provides uncertain fluxes. The 1.26 and 1.64 \(\mu\)m transitions are the highest S/N of the [Fe \(\text{II}\)] lines, with all other detected lines approximately an order of magnitude fainter. Table 4 lists the observed [Fe \(\text{II}\)] fluxes (1.26, 1.29, 1.59, 1.64, and 1.66 \(\mu\)m) and intensity-weighted radial velocities for various knots marked in Figure 6. We subtracted the airglow contamination for the 1.64 \(\mu\)m fluxes in Table 4 by estimating the airglow contamination using the same aperture on a nearby [Fe \(\text{II}\)]-free part of the sky and

Figure 6. (Left) \(H_2\) 1-0 S(1) integrated intensity map with the red elliptical regions showing the features marked in the Tables 1–3. (Right) [Fe \(\text{II}\)] 1.26 \(\mu\)m integrated intensity map with the red elliptical regions showing the features listed in Table 4. The cyan square, magenta triangle, and green X mark the locations of the BN object, source I, and source n, respectively. The red squares mark the locations of V2248 Ori (northwest) and MT Ori (southeast).

Figure 7. (Left) [Fe \(\text{II}\)] 1.26 \(\mu\)m integrated intensity map. (Right) [O I] 1.32 \(\mu\)m integrated intensity map. The cyan square, magenta triangle, and green X mark the locations of the BN object, source I, and source n, respectively. The red squares mark the locations of V2248 Ori (northwest) and MT Ori (southeast).
subtracting. We note that the radial velocity measurements for
[Fe II] have uncertainties of ±40 km s\(^{-1}\). Unlike for the
H\(_2\) radial velocities, we chose to report the radial velocity not
as the median value among the observed transitions but as the
value for the highest S/N transition (1.26 \(\mu\)m); there was
significance disagreement in the radial velocity measurements
among the [Fe II] transitions.

### 3.3. Ionization Front and PDR

We detect emission from O, Fe\(^{+}\), and P\(^{+}\) (singly ionized
phosphorus) originating from the ionization front and PDR
northeast of the Trapezium cluster, between the foreground M42
H\(_{2}\) region and the background Orion A molecular cloud and
OMC1 cloud core. These atomic transitions are excited by far-UV
radiation from the foreground Trapezium stars at the surface of
the molecular cloud in which the BN/KL outflow is embedded.
Specifically, we detect in emission the 1.3164 \(\mu\)m [O I] line
(Marconi et al. 1998; Smith & Hartigan 2006), the [Fe II] lines at
1.256 and 1.644 \(\mu\)m and their related transitions, and 1.18877 \(\mu\)m [P II] (Rudy et al. 1991, 2001). Except for [O I] and
[Fe II] at 1.256 \(\mu\)m, the lines are low S/N and integrated intensity
maps could not be made.

With the PDR tracers, we detect an ionized feature oriented in
the east-west direction at \(\delta = -5:22:20\) called the “E-W
Bright Bar” by García-Díaz & Henney (2007). At \(\delta = -5:23:12\) is the “Trapezium Compact Bar”, also in the
east-west direction (García-Díaz & Henney 2007), and the
Trapezium cluster resides in the 20\(^{\circ}\) missing box of data to the
east at \(\alpha = 5:35:16\). The atomic emission associated with these
features is redshifted, \(v_{\text{LSR}} = +15-30\) km s\(^{-1}\).

These PDRs have been detected in many other tracers
including recent velocity-resolved C\(^{+}\) observations with
Herschel (Goicoechea et al. 2015a) that detect the large “East
PDR” of which the E–W Bright Bar is only a small, western
section. Goicoechea et al. (2015a) detects C\(^{+}\) at
\(v_{\text{LSR}} = +9.5\) km s\(^{-1}\) with a typical line-width of 4–5 km s\(^{-1}\),
consistent within errors with this paper’s radial velocity
measurement (\(v_{\text{LSR}} = +15-30\) km s\(^{-1}\)).

### 3.4. Source I and BN Reflection Nebulae

Polarization studies by Hough et al. (1986) and Burton et al.
(1991) showed that there is a diffuse H\(_2\) reflection nebula
surrounding the BN/KL outflow produced by the H\(_2\) Peaks 1 and
2 (Beckwith et al. 1978), and continuum reflection nebulae
caused mainly by source I. The J-, H-, and K-band continuum
image (free of emission lines) in Figure 8 shows the reflection
nebulae surrounding source I and the BN object. Polarization
studies have confirmed that the K-band continuum is produced
by scattered light the young protostars source I and BN
offset aligned dust grains (e.g., Hough et al. 1986). The J- and
H-band continuum is dominated by scattered light from the
bluer Trapezium stars, but we lack the sensitivity to detect this.

We extracted a spectrum of source I’s reflection nebula to the
east, using a larger aperture than Morino et al. (1998) and Testi
et al. (2010), and confirmed the presence of CO bandheads in
absorption at \(\lambda > 2.29\ \mu\)m (Figure 9). There is an unidentified
absorption line at 2.317 \(\mu\)m that could be an artifact, because it is
coincident with an airglow line. CO absorption indicates a
cold photosphere for source I (\(T < 5500\) K), but could also be
dominated by the cool “photosphere” of a circumstellar disk
(Morino et al. 1998; Testi et al. 2010). Our spectra do not reach
sufficient depth to detect any other photospheric lines. Because
source I and the BN object are widely accepted as the sources
of the BN/KL outflow, characterizing them is essential for
distinguishing between the current models of the outflow’s
origin (e.g., Tan 2004, Bally & Zinnecker 2005, and Bally
et al. 2015).

The spectrum of BN’s reflection nebula exhibits Br\(\gamma\) and
He\(\iota\) (2.05 \(\mu\)m) absorption, confirming BN’s consistency with a
late-O/early-B type star (Scoville et al. 1983; Hanson et al.
1996), but is not of sufficient depth to detect other features.

### 3.5. Jets and Disks

Several Herbig Haro objects and other YSO jets are visible
in H\(_2\), H\(_{\alpha}\), He\(\iota\), and [Fe II] and are discussed further in this
section.
3.5.1. HH 201

HH 201 (5:35:11.393, −5:21:53.97) is a well-studied Herbig Haro object of the same dynamical origin as other fingers in the BN/KL outflow (Doi et al. 2004). It is the brightest of the knots in both the optical (Münch & Taylor 1974) and near-IR [Fe II] (Bally et al. 2015), but has only faint H2 emission (Graham et al. 2003) indicating that HH 201 lies in the foreground PDR.

The peak [Fe II] emission occurs at the fingertip (the northwest end) and is blueshifted ($v_{\text{LSR}} = −80$ km s$^{-1}$), indicating this knot is moving out of the OMC1 cloud core into the PDR. In the optical (Hα and [S II]), HH 201’s radial velocity is about $−270$ km s$^{-1}$ (Graham et al. 2003; Doi et al. 2004), and this value agrees with the velocity [Fe II] and Paβ first appear in the PPV cube. It is possible that HH 201 is the brightest [Fe II] source because iron’s gas phase abundance is increased in the PDR (Section 3.2).

HH 201’s [Fe II] line profiles show an asymmetric line shape with a blue tail (Figure 10). Doi et al. (2004) showed HH 201 is a superposition of two bowshocks, explaining the asymmetry of the line profiles. The ratio of HH 201’s proper motion ~170 km s$^{-1}$ (Hu 1996) to its radial velocity suggests that HH 201 is inclined ~60° to our line of sight, assuming the tilt of the knot away from the plane of the sky is given by $\theta_{\text{jet}} = \tan^{-1}(V_r/V_{PM})$, where $V_r$ is the average radial velocity and $V_{PM}$ is the proper motion.

In Figure 6, HH 210 is marked as “[Fe II]−10” in the left panel and “10” in the right panel. It slightly overlaps with the H2 feature #25-W, which has the same position angle and is located to the southeast. #25-W is redshifted ($v_{\text{LSR}} = +22$ km s$^{-1}$), in stark contrast to HH 210. #25-W has a visual extinction 2–3 mag greater than its surroundings, while HH 210’s extinction does not stand out (Figure 3). Because HH 201’s source is thought to be the same as the BN/KL outflow and the two are not bright in the same tracers, it is unlikely #25-W and HH 201 are associated.

3.5.2. HH 202

HH 202 (5:35:11.640, −5:22:55.25) is a fully ionized jet not associated dynamically with the BN/KL outflow. Its source is unknown, although it may share a common origin with other nearby Herbig Haro objects (O’Dell et al. 1997). Photoionization by the Trapezium cluster is its primary excitation mechanism with negligible shock excitation (O’Dell et al. 1997) and significant departures from Case B recombination (Mesa-Delgado et al. 2009). HH 202 shows extended emission in many tracers including H1 Paβ, the Brackett and Pfund series, He I, [Fe II], [O I], and [Fe II] (Figure 11).

3.5.3. HH 210

HH 210 is a knot at (5:35:15.430, −5:20:39.95) of the BN/KL outflow and is only detected in [Fe II] and H1. It is the only known Herbig Haro object associated with soft X-ray emission (COUP 703 and COUP 704; Grosso et al. 2006). HH 210 has the highest proper motion of all the BN/KL fingers (309–425 km s$^{-1}$; Doi et al. 2002) and, along with HH 201 (Section 3.5.1), is among the few visible at optical wavelengths as it lies in front of the dense gas in which the rest of the fingers are embedded. HH 210 is visible in almost all [Fe II] lines in the J and H bands, H1 Brγ and Paβ (Figure 12). We detect two kinematically distinct components in [Fe II] emission that peak at $v_{\text{LSR}} = −260$ and −30 km s$^{-1}$ (Figure 13). The lack of H2 emission also indicates that HH 210 lies in the PDR, agreeing with its blueshifted emission.

Like HH 201, the PDR’s presence might explain HH 210’s high [Fe II] intensity, and its double peaked line profile and dual soft X-ray counterparts suggest that it is the superposition of two bowshocks. Combined with Doi et al. (2002)’s proper motion measurement of 309–425 km s$^{-1}$, the radial velocities suggest the two bowshocks’ full velocity vectors are separated...
by ~20°. The blueshifted component appears less spatially extended than the slower-moving redshifted component (Figure 13) possibly because Fe⁺ is ionized to Fe⁺⁺ so the [Fe II] emission measure is smaller.

3.5.4. OMC-1n

A CO jet emitted from a protostar associated with the OMC-1n dense filaments may be visible in H₂ in the northeast corner of the PPV cube. Figure 14 shows the overlap of CO (2-1) emission detected with the Submillimeter Array (SMA; Teixeira et al. 2016) and lobes of near-IR H₂ emission that do not appear to be kinematically associated with the BN/KL outflow. In this ~40° region around (5:35:15.5, −5:21:54.8), the CO and H₂ emission do not appear to coincide perfectly, but given Teixeira et al. (2016)’s 3″ pointing-accuracy estimate and our 1″-accurate WCS solution (which corresponds to 1 pixel...
accuracy given our 1 arcmin pixel−1 pixel scale, overlap in the plane-of-the-sky is reasonable. They also coincide in velocity space. The H2 double-lobe seen in Figure 14 around (5:35:15, −5:20:40) appears over v_LSR = +22–34 km s−1, and the redshifted CO emission appears over v_LSR = 0–40 km s−1. South of the H2 double-lobe is a faint circle of H2 emission with radius 3′75 (1500 au at 414 pc), which may be the walls of a cavity evacuated by the jet.

3.5.5. V2270 Ori

The V2270 Ori (05:35:15.394, −05:21:14.11) bipolar outflow detected in the adaptive optics [Fe II] image of Bally et al. (2015) is also detected in this data set (Figure 15). The southwestern part of the jet is redshifted, and the northeastern jet is blueshifted. When applying our Gaussian fitting routine to this region, we find for the redshifted jet intensity-weighted v_LSR ≈ +100 km s−1 with respect to the rest frame of the...
contours show emission with velocities from levels ranging from 9 to 30 Jy beam$^{-1}$ to have a velocity gradient extending from approximately from 14 to 140 Jy beam$^{-1}$. Because V2270 Ori’s jet has low S/N in our observations, the velocity centroid measurements are large.

Figure 14. OMC-1n jets visible in the northeast corner of our PPV cube. Shown in grayscale is a single channel from the K-band PPV cube at $\lambda = 21219.7$ Å ($\Delta \lambda = 2.88$ Å). We do not show the H$_2$ 1-0 S(1) integrated intensity map, because the S/N is low in the northeast corner of the map, so many of the Gaussian fits to the 1-0 S(1) line were not robust. The contours show CO (2-1) emission from Teixeira et al. (2016). The red contours show emission with velocities from 0 to +40 km s$^{-1}$, with contour levels ranging from 14 to 140 Jy beam$^{-1}$ km s$^{-1}$ in steps of 14 Jy beam$^{-1}$ km s$^{-1}$. The blue contours show emission with velocities from –20 to 0 km s$^{-1}$, with contour levels ranging from 9 to 30 Jy beam$^{-1}$ km s$^{-1}$ in steps of 3 Jy beam$^{-1}$ km s$^{-1}$. The SMA’s 3″ synthesized beam is shown in black in the upper right corner.

Figure 15. PV diagram of the V2270 Ori [Fe ii] (1.64 μm) bipolar jet. The position axis (labeled “Offset”) is centered on V2270 Ori, and the velocity axis is centered on the [Fe ii] line’s vacuum rest wavelength (1.6439 μm). The blueshifted jet is centered around –100 km s$^{-1}$, and the redshifted jet appears to have a velocity gradient extending from approximately +125 km s$^{-1}$ near the star, to +65 km s$^{-1}$ away from the star. The uncertainties in these velocities are large.

Orion Nebula [Fe ii] emission, and $v_{LSR} \approx -25$ km s$^{-1}$ for the blueshifted jet. Using a position–velocity (PV) diagram, we find that the redshifted jet shows a negative velocity gradient extending from approximately +125 km s$^{-1}$ near the star, to +65 km s$^{-1}$ away from the star. The blueshifted jet is centered around –100 km s$^{-1}$. Because V2270 Ori’s jet has low S/N in our observations, the velocity centroid measurements are large.

4. SUMMARY

We have presented near-IR (1.1–2.4 μm) PPV cubes of the Orion BN/KL outflow and integrated intensity and kinematic maps in 13 H$_2$ and 4 [Fe ii] lines. The kinematic maps have clarified the velocity structure of the 500 year old, wide-angle outflow. In the central arcminute of the flow, the H$_2$ emission is dominated by blueshifted fingers and knots on the near-side of the flow. When combined with proper motion measurements from Bally et al. (2015), we see that most of the outer fingers’ motion lies predominantly in the plane of the sky, save for a few knots and fingers that exhibit significant redshift. The redshifted features correspond to regions of low extinction, indicating that they are on the far side of the flow and are seen through a cavity in the dense gas.

We also present tables of H$_2$ and [Fe ii] flux ratios for a sample of features and a pixel-by-pixel flux ratio map for the H$_2$ 1-0 S(1) and 2-1 S(1) transitions. The 1-0 S(1)/2-1 S(1) line ratios are consistent with shock excitation, although in the outer regions of the flow, the ratios indicate that UV excitation is present but not dominant. These line ratios (presented as observed and dereddened) can be used for modeling with shock or PDR codes to derive the true excitation conditions of the BN/KL outflow.

Present in the PPV cubes are several bright YSO jets that we highlight: HH 201, HH 202, HH 210, V2270 Ori, and two protostellar jets north of HH 210. We also detect two ionization fronts and PDRs and the reflection nebulae surrounding source I and the BN object.

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- aplpy (http://aplpy.github.io)
- astropy (Robitaille et al. 2013)
- ipython (http://ipython.org/)
- molecular-hydrogen (https://github.com/keflavich/molecular_hydrogen)
- pvextractor (http://pvextractor.readthedocs.org/)
- pyregion (http://pyregion.readthedocs.org/)
- pyspeckit (Ginsburg & Mirocha 2011)
- scicatalog (https://github.com/parkus/scicatalog)
- sdpy (https://github.com/keflavich/sdpy)
- spectral-cube (http://spectral-cube.readthedocs.org/)
- wcsaxes (wcsaxes.rtfd.org)

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Bally, J., & Zinnecker, H. 2005, AJ, 129, 2281
