DETAILED X-RAY LINE PROPERTIES OF $\theta^2$ Ori A IN QUIESCENCE

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Received 2010 September 8; accepted 2011 March 21; published 2011 May 20

ABSTRACT

We investigate X-ray emission properties of the peculiar X-ray source $\theta^2$ Ori A in the Orion Trapezium region using more than 500 ks of HETGS spectral data in the quiescent state. The amount of exposure provides tight constraints on several important diagnostics involving O, Ne, Mg, and Si line flux ratios from He-like ion triplets, resonance line ratios of the H- and He-like lines, and line widths. Accounting for the influence of the strong UV radiation field of the O9.5V star, we can now place the He-like line origin well within two stellar radii of the O-star's surface. The lines are resolved with average line widths of $341 \pm 38$ km s$^{-1}$. In the framework of standard wind models, this likely implies a rather weak wind with moderate post-shock velocities. The emission measure distribution of the X-ray spectrum, as reported previously, includes very high temperature components which are not easily explained in this framework. The X-ray properties are also not consistent with coronal emissions from an unseen low-mass companion nor with typical signatures from colliding wind interactions. The properties are more consistent with X-ray signatures observed in the massive Trapezium star $\theta^1$ Ori C which has recently been successfully modeled with a magnetically confined wind model.

Key words: stars: individual ($\theta^2$ Ori A) – stars: magnetic field – stars: winds, outflows – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

$\theta^2$ Ori A is a triple star system at the heart of the Orion Nebula Cluster (ONC). Its massive primary has been identified as a fifth magnitude O9.5V star (Abt et al. 1991) with a mass of 25 $M_\odot$ (Preibisch et al. 1999), making it the second most massive star in the ONC next to the 45 $M_\odot$ O5.5 V star in $\theta^1$ Ori C. A more recent photometric study provides an optical identification of O9 V and a total system mass of $39 \pm 14$ $M_\odot$ (Simón-Díaz et al. 2006). The studies of Abt et al. (1991) and Preibisch et al. (1999) show that this system includes two close intermediate mass companions at 173 AU and 0.47 AU separation with mass estimates between 7 and 9 $M_\odot$ for each.

$\theta^2$ Ori A has been extensively monitored in X-rays with the Chandra X-ray Observatory and has shown its fair share of odd behavior. Observations in 2000 showed that the X-ray source exhibited unusual and dramatic variability with a 50% flux drop in less than 12 hr accompanied by multiple small flares with only a few hours durations (Feigelson et al. 2002). Such flaring in an early-type stellar system is surprising since this cannot be explained by the standard wind shock models for X-rays in early-type stars (Lucy 1982; Owocci et al. 1988), nor by the magnetically confined wind models (MCWMs; Babel & Montmerle 1997). While the MCWM can produce hard X-ray emission like those observed in $\theta^1$ Ori C (Schulz et al. 2000, 2003; Gagné et al. 2005) and r Sco (Cohen et al. 2003), it does not explain the observed outbursts in $\theta^2$ Ori A. At the time, the suggestion was made that such emission could be the result of magnetic reconnection events. To add to this excitement, a specifically powerful X-ray flare from $\theta^2$ Ori A, seen with the Chandra High Energy Transmission Grating Spectrometer (HETGS), surprised observers in 2004 (Schulz et al. 2006) with total output exceeding $10^{37}$ erg. Considering the orbital phase of the close spectroscopic companion, the low He-like forbidden/intercombination line ratios, and the fact that all lines remained unresolved led to the argument that these events are triggered by magnetic interactions with the close companion. A sub-pixel re-analysis of a similar flare event which appeared during observations in the Chandra Orion Ultradeep Project (COUP; Stelzer et al. 2005; Schulz et al. 2006) in 2003, however, seems to indicate that these events may originate from the companion instead (M. Gagné 2006, private communication). An unseen T Tauri companion appears unlikely due to the observed peculiar line properties with respect to the forbidden to intercombination line ratios (see Section 2.2, specifically those of Si XIII).

In contrast to that observed in the elevated states, the quiescent spectrum of $\theta^2$ Ori A exhibits temperatures above 25 MK and has line ratios which suggest that the X-ray emitting plasma is close enough to the stellar surface of the massive star to argue for some form of magnetic confinement (Schulz et al. 2006). The argument is strengthened by the fact that the line widths, quite in contrast to the narrow line widths observed during the outbursts, seem broadened to the order of 300 km s$^{-1}$. These properties are very reminiscent of the MCWM results obtained in $\theta^1$ Ori C (Gagné et al. 2005), where, through detailed simulations, it was demonstrated that the bulk of the emitting plasma is close to the photosphere, or within $\sim 2 R_*$, and line widths are $\lesssim 400$ km s$^{-1}$. However, in spite of these apparent differences, the properties of the quiescent state remained fairly unconstrained with respect to precise line ratios and widths. $\theta^2$ Ori A’s quiescent X-ray luminosity is about an order of magnitude lower than that observed during outburst and the study remained statistically limited.

The Chandra Data Archive (CDA)$^4$ now contains an additional $\sim 300$ ks on $\theta^2$ Ori A between 2004 and 2008 and in this paper we present a full analysis of the quiescent spectrum allowing us to derive much better constrained line properties.

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The Astrophysical Journal, 734:14 (8pp), 2011 June 10
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Figure 1. Counts spectrum from the total combined data on θ² Ori A (MEG+HEG).

Table 1
Observation Log

| Sequence Number | ObsID | Start Date (UT) | Start Time (UT) | Exposure (ks) | Count Rate (10⁻² counts s⁻¹) | Offset (arcmin) | Phase Range⁵ |
|-----------------|-------|-----------------|-----------------|--------------|-----------------------------|----------------|--------------|
| 200001          | 3     | 1999 Oct 31     | 05:58:56        | 49.6         | 2.33                        | 2.42           | 0.76–0.79    |
| 200002          | 4     | 1999 Nov 24     | 05:39:24        | 30.9         | 3.64                        | 2.28           | 0.92–0.99    |
| 200175          | 2567  | 2001 Dec 28     | 12:25:56        | 46.4         | 2.72                        | 1.98           | 0.99–1.01    |
| 200176          | 2568  | 2002 Feb 19     | 20:29:42        | 46.3         | 2.55                        | 2.10           | 0.53–0.55    |
| 200242          | 4473  | 2004 Nov 3      | 01:48:04        | 49.1         | 1.86                        | 1.26           | 1.00–1.03    |
| 200243          | 4474  | 2004 Nov-23     | 07:48:38        | 50.8         | 18.35                       | 1.39           | 0.96–0.99    |
| 200420          | 7407  | 2006 Dec 3      | 19:07:48        | 24.6         | 1.78                        | 1.64           | 0.27–0.29    |
| 200423          | 7410  | 2006 Dec 6      | 12:11:37        | 13.1         | 1.38                        | 1.07           | 0.40–0.41    |
| 200421          | 7408  | 2006 Dec 19     | 14:17:30        | 25.0         | 2.38                        | 2.08           | 0.02–0.04    |
| 200422          | 7409  | 2006 Dec 23     | 00:47:40        | 27.1         | 2.18                        | 2.30           | 0.19–0.21    |
| 200424          | 7411  | 2007 Jul 27     | 20:41:22        | 24.6         | 2.40                        | 3.94           | 0.53–0.54    |
| 200425          | 7412  | 2007 Jul 28     | 06:16:09        | 25.2         | 2.10                        | 4.39           | 0.55–0.56    |
| 200462          | 8568  | 2007 Aug 6      | 06:54:08        | 36.1         | 2.37                        | 2.53           | 0.98–1.00    |
| 200462          | 8589  | 2007 Aug 8      | 21:30:35        | 50.7         | 2.27                        | 2.53           | 0.10–0.13    |
| 200478          | 8897  | 2007 Nov 15     | 10:03:16        | 23.7         | 2.25                        | 3.37           | 0.80–0.81    |
| 200477          | 8896  | 2007 Nov 30     | 21:58:33        | 22.7         | 2.65                        | 2.34           | 0.54–0.55    |
| 200476          | 8895  | 2007 Dec 7      | 03:14:07        | 25.0         | 2.00                        | 1.74           | 0.84–0.85    |

Notes.
- θ² Ori A zeroth-order position offset from nominal pointing.
- Assuming a 20.974 day period and periastron passage at HJD₀ = 2440581.27 (Abt et al. 1991).
- 4474 is included here only for reference; no analysis herein utilized it due to the extremely elevated count rate during its entirety.

The results are also used to test the hypothesis that the X-ray emission from θ² Ori A is consistent with predictions from the MCWM. The paper is structured as follows. In Section 2 we discuss the observations and analysis methods, in Section 3 we discuss the results of our emission line measurements, and finally we summarize our findings in Section 4.

2. OBSERVATIONS AND ANALYSIS

We have retrieved Chandra HETGS data in the vicinity of the ONC, which were originally observed as a part of the HETG Orion Legacy Project (Schulz et al. 2008), from the CDA. There are now 17 separate Chandra observations which include θ² Ori A within an off-axis angle suitable for extraction. See Table 1 for a list of the included observations and selected properties. Noting that this study is focused on the quiescent state spectrum and that ObsID 4474 was not included in any analysis in the current study due to the substantially elevated count rate during its entire exposure, we have accumulated 520 ks of exposure time on θ² Ori A in the quiescent state. Figure 1 shows the total combined counts spectrum using the 520 ks on θ² Ori A.

As noted, none of these observations were targeted at θ² Ori A; indeed no Chandra gratings observations have ever targeted θ² Ori A. However, using the suite of advanced extraction tools provided by the Chandra Transmissions Grating Catalog and Archive (TGCat; Huenemoerder et al. 2011; Mitschang et al. 2010)⁵, extraction of the dispersed counts of off-axis X-ray source positions proved to be trivial.

Grating spectra were extracted and responses computed using the TGCat software to locate the optimal centroid position of θ² Ori A and apply proper calibration for each observation. In a crowded field such as the Orion Trapezium, careful attention must be paid during analysis to contamination from other zeroth-order counts lying close to or on top of dispersion counts and dispersion arms crossing one another at critical points. The intrinsic energy resolution of the ACIS detector makes it possible to disambiguate the source of a photon at a particular dispersion angle based on the CCD resolution energy of that photon. Thus, in order to identify contamination, we reviewed order sorting images (ACIS CCD event energy

⁵ http://tgcat.mit.edu
versus gratings order × wavelength, or specifically FITS-file columns TG,MLAM versus ENERGY) for each observation and identified potential contamination. In this view, the source traces two hyperbolas centered on $m \lambda = 0$ (e.g., see Chandra POG\(^7\); their Figure 8.13); traces from confusing sources show as offset hyperbolas (dispersed) or vertical lines (zeroth order). We found no significant source of contamination in the regions used for line fitting; see Table 2 for details on the locations of these regions. Similarly, when fitting the continuum we used a set of wavelength ranges containing few lines, the “line-free regions,” in which we found little contamination. See Section 2.1 for a more detailed discussion on the continuum modeling and Section 2.2 on line fitting. Line width analysis is treated for a more detailed discussion on the continuum modeling regions, “in which we found little contamination. See Section 2.1.

Table 2

| Ion   | $z$ \(^b\) (Å) | Flux \(^{c}\) \((10^{-6} \text{ photons}^{-1} \text{ cm}^{-2})\) | $G$ | $R$ | $R_{\alpha}$ | $v_{\text{hel}}$  |
|-------|----------------|---------------------------------|----|----|-------------|----------------|
| Si xiii | 6.650          | 1.3 ± 0.3                        | 1.1 ± 0.3 | 1.7 ± 0.4 | 2.0 | 491 ± 120  |
| Mg xi  | 9.171          | 4.8 ± 0.6                        | 1.0 ± 0.1 | 1.7 ± 0.1 | 2.6 | 432 ± 53   |
| Ne ix  | 13.448         | 28.9 ± 3.3                       | 1.2 ± 0.1 | 1.7 ± 0.4 | 3.3 | 228 ± 34   |
| O viii | 21.602         | 147.3 ± 40.9                     | 0.9 ± 0.3 | <0.09 | 3.8 | 274 ± 83   |
| Si xiv | 6.187          | 0.4 ± 0.2                        | 0.3 ± 0.2 | <686  |              |                |
| Mg x   | 8.423          | 0.8 ± 0.3                        | 0.2 ± 0.1 | <518  |              |                |
| Ne x   | 12.133         | 20.0 ± 2.9                       | 0.7 ± 0.1 | 315 ± 43 |              |                |
| O vii  | 18.971         | 164.7 ± 22.3                     | 1.1 ± 0.4 | 327 ± 53 |              |                |

Notes.

\(^{a}\) All reported uncertainties are 90% confidence limits.

\(^{b}\) Measured position of resonance line for He-like triplet line groups.

\(^{c}\) Flux is that of the resonance line only for He-like triplet line groups.

\(^{d}\) For H-like Ly$\alpha$ lines this is the ratio of the H-like Ly$\alpha$ flux to He-like resonance line flux of the corresponding ion.

\(^{e}\) Computed from Chianti 6.0.1 emissivities according to Equation (1) at $G$-ratio derived temperatures (see Table 3).

All fitting of data was done using the Interactive Spectral Interpretation System (ISIS; Houck & Denicola 2000)\(^6\), along with the Astrophysical Plasma Emission Database (APED; Smith et al. 2001)\(^6\) for line emissivities and continuum modeling.

### 2.1. Continuum

The continuum emission of $\theta^2$ Ori A was modeled by fitting a single temperature APED model to the combined Medium Energy Grating (MEG)+High Energy Grating (HEG) counts for all observations to improve statistics. In order to fit only the continuum emission, we selected a set of narrow bands, considered free of significant line emission, specifically 2.00–2.95 Å, 4.4–4.6 Å, 5.3–6.0 Å, 7.5–7.8 Å, 12.5–12.7 Å, and 19.1–20 Å (e.g., see Testa et al. 2007). We assumed a hydrogen column density ($N_{\text{H}}$) of $2 \times 10^{21}$ cm$^{-2}$. Potential contamination resulting from cross-dispersion or zeroth-order confusion was mitigated in these regions by simply ignoring the affected region of an individual order during the computation of the fit. The resulting continuum model, yielding a temperature of 27 MK, was then used when fitting lines.

### 2.2. Line Fluxes and Ratios

The $f$ (forbidden, intercombination, and resonance) line ratios given by $R = f / f_{\alpha}$ and $G = (f + i) / r$ have been shown to be probes of both density ($R$) and temperature ($G$) (Gabriel & Jordan 1969) in X-ray emitting plasmas, and in the presence of a strong UV radiation field, such as is typical in O stars like $\theta^2$ Ori A, Waldron & Cassinelli (2001) demonstrated that the $R$ value rather acts as a proxy for the radial distance of X-ray emission from the stellar surface. Specifically for the $R$-ratio, it is also important to make the comparison between the observed ratio and that of the low-density limit. Blumenthal et al. (1972) showed that

$$R = \frac{R_0}{1 + \frac{\phi}{\phi_c} + \frac{n}{n_c}},$$

where $\phi / \phi_c$ is a measure of the photoexcitation, $n / n_c$ is a measure of the density, and $R_0, \phi_c, n_c$ depend only on atomic parameters and temperature. It is easily seen from Equation (1) that, ignoring photoexcitation, $R_0 = R$ when $n / n_c \ll 1$ and thus represents the low-density limit. We have computed $R_0$ using emissivities in the Chianti\(^9\) version 6.0.1 atomic database (Dere et al. 1997, 2009) and temperatures derived from the $G$ ratio given in Table 3, also computed using Chianti, for each $f$ line and list them in Table 2.

Table 3

| Ion   | log $T$ (H/He) | log $T$ (G) |
|-------|----------------|-------------|
| O vii | 6.61 (6.36, 6.44) | 6.3 (6.0, 6.5) |
| Ne ix | 6.62 (6.60, 6.64) | 6.1 (6.0, 6.3) |
| Mg xi | 6.70 (6.65, 6.72) | 6.5 (6.3, 6.6) |
| Si xiii | 6.96 (6.87, 7.02) | 6.4 (6.0, 6.8) |

\(^{6}\) http://cxc.harvard.edu/proposer/POG/

\(^{7}\) http://space.mit.edu/CXCisis

\(^{8}\) http://www.atomdb.org

\(^{9}\) http://www.chianti.rl.ac.uk/index.html
flux equaling 13% of the flux of a prominent Fe xvi line at 15.01 Å (e.g., see Walborn et al. 2009). Additionally, the Mg Ly-series converges at the centroid position of the Si xiii f-line where we assumed, based on the theoretical relative line strengths, the observed flux was overestimated by 10% of the measured flux of the isolated H-like Mg xii Lyα line. Finally, the Ne x Ly series converges upon the Mg xi i-line where there is blending of the limit of that series with the Mg xi i-line. In order to address this, we modeled the Ne x Ly series based on a fit to the isolated Ne x Lyβ line at 9.48 Å where fluxes of subsequent lines in the series were scaled based again on theoretical relative strengths.

When fitting the He-like fir triplet lines, the relative separations of the lines were fixed and the positions of the resonance lines were constrained by their rest positions. The line widths of each component for a given group were tied to one another. Where available, we fit using both MEG and HEG counts, where MEG counts were re-binned onto the HEG grid whose intrinsic channel size is half that of the MEG. Fits were performed by applying Gaussian functions for each contributing line. The G- and R-ratios were computed directly during the fitting procedure and the fir fluxes were treated co-dependently. The instrumental profile was included as calibration data while the excess width was included as a Gaussian turbulent broadening term (v_turb).

In Figures 2 and 3, the triplet regions are shown with residuals, overplotted models, and computed confidence contours.

2.3. Line Widths

Due to the degradation of Chandra image quality at off-axis angles, the HETG resolving power likewise decreases. Though the point spread function is well defined across the ACIS detector, this degradation becomes a problem for gratings because, owing to the complexity of modeling, responses are only calibrated for zeroth-order positions at the instrument nominal pointing.

This effect can be critical in line width measurements which may include a significant instrumental broadening signature. Our flux measurements are unaffected by the broadening, and we have utilized as much available data as possible to improve statistics. Four of our observations are at off-axis angles greater than the others, in particular θ² Ori A is greater than 3′ off-axis in ObsIDs 7410, 7411, 7412, and 8897. We have chosen to ignore counts in these ObsIDs during computation of line width parameters. There are two exceptions: Si xiv and Mg xii where statistics are too poor in the absence of extra counts to...
obtain reasonable measurements. In these cases, we provide upper limits on the line widths.

The average offset of our data is 2′.1 which is around the location where degradation becomes noticeable. Based on analysis of ACIS zeroth-order line response functions (LRFs) at large axial offsets (e.g., see Chandra POG), we estimate that our reported line widths are on the order of up to ∼5% broader than that of identical on-axis profiles.

To further confirm our measured broadening, we show a comparison between an unresolved Gaussian model, which includes both the $2p^2 P_{3/2}$ and $2p^2 P_{1/2}$ to $1s^2 S_{1/2}$ line transitions, since combined they can appear broadened, and our best-fit Gaussian model with a resolved width of 338 km s$^{-1}$, both folded through the instrument response, for the prominent unblended O viii emission line in Figure 4. The residuals clearly show an excess of flux at velocities corresponding to our measured width for the delta function case.

### 3. DISCUSSION

The exposure obtained from the Chandra archive of θ$^2$ Ori A represents the deepest combined high-resolution spectroscopic data set on this young massive O-star to date. The long exposure provides high statistics in critical emission lines, allowing us to diagnose its X-ray stellar wind properties beyond the 3σ level. In a previous study, Schulz et al. (2006) provided some preliminary results for the quiescent state for less than half of the current exposure. This limited measurements of critical line fluxes and widths to uncertainties larger than 50%. Our new analysis greatly reduces these uncertainties to the order of 20%.

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Figure 3. Confidence contours for measured $G$- and $R$-ratios for, clockwise from top left, Si xiii, Mg xi, O vii, Ne ix. The red inner contours show 1σ, green middle contours show 2σ, and outer blue contours show 3σ confidences.

(A color version of this figure is available in the online journal.)

Figure 4. Best-fit model and residuals for an exemplary prominent line, O viii, are plotted in red while a unresolved Gaussian model and residuals are shown in blue for comparison. The surplus in residuals on the wings of the unresolved Gaussian clearly indicates broadening of the line.

(A color version of this figure is available in the online journal.)
For example, while the previous analysis could only speculate about possible line broadening of the order of 300 km s\(^{-1}\), we now clearly resolve the lines to values between 228 ± 34 km s\(^{-1}\) for Ne IX and 491 ± 120 km s\(^{-1}\) for Si XIX, with an average of all lines of 341 ± 38 km s\(^{-1}\). Likewise critical line ratios such as the \(R\)-ratios are significantly improved, specifically for the cases of Mg XI with 0.3 ± 0.09 and Si XIX with 1.7 ± 0.4; for the case of O VII since its \(f\)-line was not detected, we now also have an upper limit.

The measured \(R\)-ratios are significantly less than \(R_0\) (Table 2). In early-type stars, this is due to the substantial UV radiation field provided by the hot photosphere (Kahn et al. 2001; Gabriel & Jordan 1969; Leutenegger et al. 2006), which for the O9.5V star in \(\theta^1\) Ori A is about 30,000 K. In this case, the \(R\)-ratio indicates the smallest distance of line formation from the stellar photosphere. We utilize this ratio to show that the X-ray line emission from \(\theta^1\) Ori A is indeed located close to the O-star’s surface. Blumenthal et al. (1972) have expressed the photoexcitation rate of the forbidden level (\(z\) or \(f\)) to the intercombination levels (\(x, y\) or \(i\)) in terms of atomic parameters. We adopt their values for the critical rates, \(\phi_c\), and use the APED for wavelengths and Einstein \(A\)-values. We assumed a uniform disk, such that the photoexcitation rate (\(\phi\) in Equation (1)) and dilution terms factor into \(\phi(r) = \phi(r = 1) \times W(r)\), in which \(r = R/R_\star\), and \(W(r) = \frac{1}{2}(1 - \sqrt{(1 - 1/r^2)})\).

We have computed the He-like line formation radii using the mean intensities for blackbodies (primarily for comparison to prior work) and using “TLUSTY” model atmosphere fluxes of Lanz & Hubeny (2003). Also for comparison with prior work, we used an effective temperature of 30,000 K, but in addition, the more recent value from Simón-Díaz et al. (2006) of 35,000 K. We used \(\log g = 4\) model atmospheres for both temperatures. The model atmospheres depart significantly from blackbodies, especially near the Lyman edge at 9.12 Å, below which photoexcitation of Si and higher-Z He-like ions occur.

Figure 5 shows the blackbody and TLUSTY computed \(R/R_\star\) values versus the modeled \(R\)-ratios, and the 90% uncertainties as given in Table 2. There is good agreement between these models for the Mg XI, Ne IX, and O VII derived ratios and 90% uncertainties. Si XIX moves inward for the TLUSTY atmospheric model as compared the blackbody, due to the lower intensity (relative to a blackbody) at the photoexciting wavelengths below the Lyman edge; for lower intensity, an origin closer to the star is required to provide enough photons for a given \(R\)-ratio. Conversely, for photoexcitation wavelengths longer than the edge (e.g., Mg XI), the model atmosphere intensity can be larger than that of a blackbody; the emission region can therefore be further from the star for a given ratio.

Regardless of the model used, the origin of emission is close to or within approximately two stellar radii from the stars’ photospheres as indicated by the vertical dotted line in Figure 5.

Another important result of our analysis is that the measured line centroid positions shown in Table 2 are, with quite high accuracy, at the expected ion rest wavelengths indicating that there are no line shifts within the Chandra sensitivity. This is an important result because any shift would indicate fast outward moving sources in a high-density wind. The line profiles appear symmetric, supporting a low-density wind assumption even though at such low broadening, profile deviations are almost impossible to trace even at our data quality.

In the case of \(\tau\) Sco (HR 6165), Cohen et al. (2003) find that lines are resolved with comparatively similar low Doppler velocities of around 300 km s\(^{-1}\). Furthermore, \(R\)-ratios are characteristic of within a few stellar radii with evidence that the X-ray emitting plasma is located more than one stellar radius above the photosphere. The type and effective temperature are very well determined as B0.2 V and 31,400 K (Kilian 1992), which closely resemble the properties of \(\theta^2\) Ori A. The temperature distribution in its HETG spectrum has components up to 25 MK. These properties, as in \(\theta^2\) Ori A, are difficult to reconcile within the standard wind model. Donati et al. (2006) discovered a medium-strength (500 G) magnetic field in \(\tau\) Sco and while such a detection has not been reported for \(\theta^2\) Ori A, a survey of magnetic fields in massive ONC cluster stars Petit...
et al. (2010) recently implied a possible upper limit of the order of 100 G. There are also a number of other massive stars of similar type which show narrow but resolved lines, though with more moderate temperatures in the X-ray spectrum, notably β Cru (Cohen et al. 2008) and σ Ori A (Skinner et al. 2008).

There are not many scenarios left which could explain our findings. We can rule out significant contributions of unseen low-mass pre-main-sequence companions by the level of the line broadening. Standard coronal emission would show unresolved lines or moderate broadening due to orbital motion (Brickhouse et al. 2001; Huenemoerder et al. 2006); neither is the case here. Colliding winds are ruled out simply by the fact that this would require an unseen massive companion with a much earlier type than the O9.5V star in θ² Ori A, which would be impossible to hide.

We find, however, quite strong similarities to the most massive star in the Orion Trapezium θ¹ Ori C (Schulz et al. 2003; Gagné et al. 2005). In the magnetically confined wind scenario, field lines of the magnetic dipole act to channel emitted material from either pole toward the magnetic equator. Simulations by Gagné et al. (2005) demonstrate that these two components meet at the magneto-equator and wind plasma with high tangential velocities reaching up to 1000 km s⁻¹ collides, generating strong shocks and elevating gas temperatures to tens of millions of degrees, thus producing the observed hard X-ray emission. Gagné et al. (2005) further demonstrate that the conditions for X-ray production are quite specific; the post shock in-falling material is rather cool, and the outflowing material’s density is too low to produce sufficient X-rays. This places a relatively tight constraint on the location of the hard X-ray emission around R ≤ 2 R*, from the stellar surface.

Another result of the simulations by Gagné et al. (2005) states that the post-shock-heated material is moving slowly, thus generating observed line profiles much narrower than expected for non-magnetic shock-heated X-ray production in O-stars (Lucy 1982; Waldron & Cassinelli 2001). In order to quantify the expected broadening, Gagné et al. (2005) recreated emission measure and line profiles from the simulations and found that the turbulent broadening is expected to be on the order of 250 km s⁻¹, with little to no blueshift in the line centroid position.

The precise effects of MCWM in terms of line properties and the derived emission origin depend, among other things, on the magnetic field strength and the wind magnetic confinement parameter η, of ud-Doula & Owocki (2002). The recent implication of an upper limit on magnetic field strength in θ² Ori A, ≤100 G compared to θ¹ Ori C with ~1000 G, provide added constraints and it would be interesting to see what modeling would reveal. Clearly, magneto-hydrodynamical (MHD) modeling would need to be invoked on θ² Ori A in order to make a more direct comparison to θ¹ Ori C (this being out of the scope of the current study); however, we do find our results to be reminiscent of the MCWM scenario in terms of line properties.

4. CONCLUSION

We have analyzed high-resolution X-ray spectra from Chandra on the young massive O star θ² Ori A, totaling over 500 ks in the quiescent state, and computed line widths and R议事 ratio for a series of prominent emission lines appearing in its spectrum. The resulting measurements show relatively narrow lines at an average width of 341 ± 38 km s⁻¹ and R议事 ratio derived X-ray emitting origin within two stellar radii. Compar-

ing these results to the simulation results of Gagné et al. (2005) for θ¹ Ori C, we argue that the X-ray production mechanism in θ² Ori A is most likely via magnetic confinement of its stellar wind outflows.

We have explored other possibilities, including standard O-star wind models and close companions, for the generation of X-rays in θ² Ori A but find that none of these are ideal for explaining the observed spectral properties. Observed line widths are too low, while shock temperatures are too high to satisfy model predictions in most of these cases.

Finally, we note that this is a comparative analysis and sets up a case for a more rigorous analysis specifically aimed at MHD using the MCWM similar to that undertaken for θ¹ Ori C.

The authors thank the anonymous referee for comments which led to improvements to this work and interesting discussions. This research has made use of data obtained from the Chandra Data Archive and software provided by the Chandra X-ray Center (CXC) in the application package CIAO. This research also made use of the Chandra Transmission Grating Catalog and Archive http://tgcat.mit.edu. Chandra is operated by the Smithsonian Astrophysical Observatory under NASA contract NAS 8-03060. This work was supported by NASA through the Smithsonian Astrophysical Observatory (SAO) contracts NAS 8-03060 and SV3-73016 for the Chandra X-ray Center and Science Instruments.

Facility: CXC

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