X-RAY AND INFRARED POINT SOURCE IDENTIFICATION AND CHARACTERISTICS IN THE EMBEDDED, MASSIVE STAR-FORMING REGION RCW 38

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ABSTRACT

We report on results of a 96.7 ks Chandra observation of one of the youngest, most embedded, and most massive young stellar clusters studied in X-rays: RCW 38. We detect 460 sources in the field, of which 360 are confirmed to be associated with the RCW 38 cluster. The cluster members range in luminosity from $10^{30}$ to $10^{33.5}$ ergs s$^{-1}$. Over 10% of the cluster members with over 100 counts exhibit flares, while about 15% of the cluster members with over 30 counts are variable. Of the sources identified as cluster members, 160 have near-infrared (NIR) counterparts either in the Two Micron All Sky Survey database or detected via Very Large Telescope observations. Of these, about 20% appear to have optically thick disks. An additional 353 members are identified through NIR observations, of which at least 50% possess optically thick disks. We fit over 100 X-ray sources as absorbed Raymond-Smith-type plasmas and find that the column to the cluster members varies from $10^{21.1}$ to $10^{23}$ cm$^{-2}$. We compare the gas to dust absorption signatures in these stars and find $N_H = A_V (2 \times 10^{21})$ cm$^{-2}$. We find that the cluster contains 31 candidate OB stars and is centered about 10" (0.1 pc) west of the primary source of the ionization, the O5 star IRS 2. The cluster has a peak central density of about 400 X-ray sources pc$^{-2}$. We estimate that the total cluster membership exceeds 2000 stars.

Key words: H ii regions — ISM: individual (RCW 38) — stars: formation — X-rays: stars

Online material: color figures, machine-readable tables

1. INTRODUCTION

The evolution of high-mass clustered star-forming regions is complex and poorly understood. Only the nearby (0.5 kpc), optically revealed Orion Nebular Cluster (ONC) is well studied. Yet a wide variety of high-mass embedded clusters are found within 2 kpc of the Sun (Lada & Lada 2003). Within this limit, the young cluster RCW 38 ($l = 268^\circ$, $b = -1^\circ$) is unique as the only region other than the ONC to contain over 1300 members. RCW 38 is significantly more embedded and spatially denser that the ONC (Smith et al. 1999) and other regions that have been studied recently with Spitzer and Chandra (e.g., Trifid [Rho et al. 2006], M17 and the Rosette Nebula [Townsley et al. 2004], and RCW 49 [Whitney et al. 2004; Churchwell et al. 2004]). RCW 38 provides a unique opportunity to study the evolution of a rich cluster during the phase in which its most massive member (O5) has just completed its ultracompact H ii region phase and is now greatly influencing its natal environment and the evolution of its low-mass members.

At a distance of 1.7 kpc, RCW 38 (Rodgers et al. 1960) is one of the brightest H ii regions at radio wavelengths (e.g., Wilson & Bolton 1960). It is a uniquely young (<1 Myr), embedded ($A_V \approx 10$) stellar cluster surrounding an early O star, IRS 2 ($\sim$O5; Frogel & Persson 1974; Smith et al. 1999). Chandra and deep near-infrared (NIR) observations reveal a dense cluster embedded in a diffuse hot plasma (Wolk et al. 2002). The O star has evacuated its immediate surroundings of dust, creating a wind bubble ~0.1 pc in radius (Smith et al. 1999; M. C. Vigil et al. 2006, in preparation) that is confined by the surrounding molecular cloud, as traced by millimeter continuum and molecular line emission (Bourke et al. 2004). This bubble is filled with diffuse thermal and synchrotron X-ray emission (Wolk et al. 2002), and diffuse emission can be traced outside of the bubble, showing a similar structure to the diffuse infrared emission in the region. At the interface between the bubble and cloud is a region of warm dust and ionized gas, which shows evidence for ongoing star formation, particularly along its western edge (Smith et al. 1999; M. C. Vigil et al. 2006, in preparation). Extended warm dust is found throughout the 2–3 pc region at mid-infrared wavelengths and coincides with the extended X-ray plasma. This is evidence that the influence of the massive stars reaches beyond the confines of the O star bubble. RCW 38 appears similar in structure to RCW 49 and M20, which have been studied with IRAC and MIPS on Spitzer (Whitney et al. 2004; Churchwell et al. 2004; Rho et al. 2006), but it is not as evolved. RCW 38 appears to be a blister compact H ii region lying just inside the edge of a giant molecular cloud.

In this paper we discuss the X-ray point sources observed in our recent Chandra and NIR observations. Section 2 describes the basic observational setup and data reduction, § 3 assesses cluster membership via quartile (X-ray color) analysis, § 4 examines X-ray source variability, and § 5 models the X-ray spectra. Both of these results are used to evaluate the effectiveness of using X-ray color as a membership criterion. In § 6 we fold in ground-based infrared data for a variety of purposes. We estimate disk parameters for the X-ray sources, as well as evaluating the full stellar content of the cluster. We further evaluate the relationship between the inferred gas and dust columns along the line of sight and examine the effect of X-ray biases in source selection. We also estimate the total size of the cluster, with special focus on the O and

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regions of interest are identified. the ellipses near the core are the "common background regions" used for sources in the core as discussed in § 2.1. In R with moderate spectral resolution (of the region. we summarize our results in the field and their implications for the three-dimensional structure of the region. we summarize our results in § 8.

2. observation and data reduction

Chandra observed RCW 38 on 2001 December 10–11 for 96.7 ks (ObsID 2556), using Advanced CCD Imaging Spectrometer (ACIS) chips 0, 1, 2, 3, 6, and 7 in very faint mode. The ACIS combines the ability to image X-rays at a 0.492 plate scale with moderate spectral resolution ($R$ ~ 30–50) and time tagging every 3.2 s. The combined field of view (FOV) of the four chips in the imaging array is 16.9' × 16.9'. The aim point of the array was $8^h59^m19.20$, $-47^\circ 30'22.0$ (J2000.0), and the satellite roll angle (i.e., orientation of the CCD array relative to the north-south direction) was 51'. The roll angle was selected so that photons from the H ii region Brα 213A would strike the ACIS spectroscopic array, whereupon chips 6 and 7 were also turned on. While the H ii region was clearly detected, these data are not discussed here, since the mirror point-spread function (PSF) is considerably degraded far off-axis. The focal plane temperature was −119.7 C. The radiation environment was benign.

2.1. data preparation

The raw data were originally processed under the Chandra X-ray Center’s (CXC) standard processing version, 6.4.0. we reprocessed the observation using the latest version, 6.13.2. using acis _ process _ events on the level 1 events files, a gain correction is applied from CALDB 2.21. The charge transfer inefficiency (CTI) correction and VFAINT background cleaning, available since version 6.12, were also applied. An energy filter was applied to remove photons above 8 keV and below 300 eV. we found that the VFAINT correction removed good events from bright sources and did not reveal any new faint sources. So the VFAINT correction was backed out, leaving only the CTI correction. Following standard processing, bad grade and bad status (grades 1, 5, and 7 and status >0) events and bad time intervals were filtered using the CIAO tool dmcopy.

Time-dependent gain corrections were applied and acis _ process _ events rerun. While there were over $3 \times 10^6$ level 1 events, our "cleaned" data file used for analysis contained 171,973 events. The central portion of these data is shown in Figure 1.

An exposure map was created using merge _ all, accurately representing the effective exposure time for a 1.7 keV photon. we chose this single energy for the exposure map, since it is intermediate between the maximum of the effective area of the High Resolution Mirror Assembly ACIS system and an estimated mean source energy of ~2.0 keV. The exposure map corrects for the changes in the effective area of the mirror as a function of off-axis distance and telescope dithering. The exposure map is later applied automatically by CIAO tools extracting count rates and spectra.

2.2. source detection

PWDetect $^2$ was used for source detection on our cleaned events list to identify sources across the entire I array. Threshold significance was set to detect sources between 4 and 5.31 equivalent Gaussian $\sigma$, and the data were searched on scales of 0.13–16' angular. With these settings, a false detection rate of <1% is expected. we did not change any PW Detect settings. Source detection was done on the whole field at once. The program did not seem to be confused by faint sources embedded in diffuse emission. PWDetect produces a regions file defining the source extent for extracting photons. These regions were adapted to more meaningful regions based on the actual Chandra PSF and chip position for each source. we used mk _ psf to obtain images of the PSF at various off-axis angles $\theta$ (arcminutes) and rotation angles $\phi$ (degrees) around the ACIS array. At each source location an ellipse was generated to enclose 95% of the total X-ray energy. This led to the following derived parameterization applied to our sources for elliptical regions around PWDetect’s returned source locations:

$$\text{major axis} = 1.97 - 0.22\theta + 0.15\theta^2,$$

$$\text{minor axis} = 2.03 - 0.13\theta + 0.08\theta^2,$$

$$\text{angle} = 95.4 + 0.47\phi.$$
This formulation was used, except as noted below, to define the extraction region for each source. Several spurious and overlapping sources were visually edited. To aid in editing unresolved and confused sources, a NIR $K_s$ image with X-ray contours overplotted proved helpful (Fig. 2). The NIR data are discussed in detail in § 6.

In most cases, background subtraction was made via background regions centered on each source. The background regions were elliptical annuli centered on the source with inner axes 2.7 times the length of the axes for the source region and outer axes 4.1 times the source region axes. The inner edge of this annulus was chosen to make certain no energy from the extended wings was included in the background. The outer axis of the background annulus was chosen to be 4.1 times the source axis to allow the maximum background area, which would not generally need to be adjusted for other sources. Background regions were manually adjusted in cases in which chip edges or other sources interfered. For areas near the center of the cluster, with several nearby sources, a common background region was created from a suitable region nearby. Sources in the central arcminute of the cluster were divided into two sectors, northwest and southeast. In each half a common two-part background was used, since diffuse emission is present in the region that changes spectrally from northwest to southeast. The two background regions are indicated by the ellipses in Figure 1.

A total of 460 sources were found on the ACIS-I array, including 31 sources with more than 200 net counts, 49 sources with 100–200 net counts, 71 sources with 50–100 net counts, and 78 sources with 20–50 net counts. Sources 95 and 228 were removed from the list as duplicates late in the analysis process, hence they are skipped in the enumeration. All X-ray sources are listed in Table 1. Column (1) of Table 1 gives the internal identification of each source, while column (2) gives the official IAU/CXC designation. Columns (3) and (4) list the right ascension and declination (J2000.0). Columns (5) and (6) list the off-axis distance in arcminutes and the net counts background-subtracted and corrected for the aperture size, respectively, while columns (7) and (8) list the number of intervals of constant flux at 95% and 99% significance requirements. While details of this last column are discussed in § 4, the key point is that more than one interval indicates a variable source.

### 3. CLUSTER MEMBERSHIP

As stars progress from class 0 to class III (Lada & Shu 1990), it is only with an unbiased sample of cluster membership that the evolution of the star+disk system can be understood. Since optical spectroscopic follow-up is not possible for such an absorbed/obscured cluster, we develop here a method of using the X-ray color and spatial properties of each source to assess the probability that it is a cluster member independent of its infrared properties. The typical method of model-independent spectral analysis is to use X-ray colors in the form of hardness ratios, $HR = (counts_H - counts_S)/(counts_H + counts_S)$, where “H” and “S” refer to the

### Table 1

**X-Ray Sources Detected in the RCW 38 Field**

| Source No. (1) | CXOJ (2) | R.A. (J2000.0) (3) | Decl. (J2000.0) (4) | Off-Axis Angle (arcsec) (5) | Net Counts (6) | Bayesian Blocks (95% sig.) (7) | Bayesian Blocks (99% sig.) (8) |
|---------------|---------|------------------|-------------------|---------------------------|----------------|-------------------------------|-------------------------------|
| 1             | 085821.3–473107 | 08 58 21.26       | −47 31 07.2       | 604.6                     | 54.1           | 1                             | 1                             |
| 2             | 085823.8–473001 | 08 58 23.77       | −47 30 01.8       | 577.1                     | 38.5           | 1                             | 1                             |
| 3             | 085827.6–473009 | 08 58 27.59       | −47 30 09.2       | 538.3                     | 68             | 1                             | 1                             |
| 4             | 085829.9–472824 | 08 58 29.89       | −47 28 24.1       | 526.6                     | 96.6           | 1                             | 1                             |
| 5             | 085830.9–473221 | 08 58 30.87       | −47 32 21.2       | 520.6                     | 28             | 1                             | 1                             |
| 6             | 085831.5–472808 | 08 58 31.51       | −47 28 08.1       | 514.3                     | 60.3           | 1                             | 1                             |
| 7             | 085833.1–473152 | 08 58 33.15       | −47 31 52.6       | 491.8                     | 24.1           | 1                             | 1                             |
| 8             | 085834.6–472816 | 08 58 34.61       | −47 28 16.5       | 481.8                     | 119.3          | 2                             | 1                             |
| 9             | 085835.1–472902 | 08 58 35.10       | −47 29 02.8       | 467.6                     | 15.6           | 1                             | 1                             |
| 10            | 085836.1–473135 | 08 58 36.11       | −47 31 35.9       | 459.2                     | 24.2           | 1                             | 1                             |
| 11            | 085836.4–473250 | 08 58 36.39       | −47 32 50.9       | 475.5                     | 64.6           | 2                             | 2                             |
| 12            | 085839.6–473126 | 08 58 39.60       | −47 31 26.7       | 422.7                     | 19.5           | 1                             | 1                             |
| 13            | 085841.6–472835 | 08 58 41.60       | −47 28 35.2       | 408.4                     | 36.6           | 1                             | 1                             |
| 14            | 085841.9–472627 | 08 58 41.92       | −47 26 27.9       | 453.5                     | 29.1           | 1                             | 1                             |
| 15            | 085842.5–473040 | 08 58 42.50       | −47 30 40.5       | 388.0                     | 10.9           | 1                             | 1                             |

**Notes.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 1 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.
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deviations from a fit to all the bright sources to the right of the vertical demarcation. See text for details.

On such a plot one can distinguish changes in temperature from absorption. Instead, we use a quartile analysis technique for model-free analysis of X-ray data explored by Hong et al. (2004). Quartile analysis avoids some biases inherent in the selection of bandpasses needed to calculate hardness ratios. In this form of quartile analysis, one starts with the full ACIS bandpass of $E_{\text{lo}} = 0.3 \text{ keV}$ and $E_{\text{up}} = 8.0 \text{ keV}$. Here $E_{\text{lo}}$ is defined as the photon energy below which $x\%$ of the photon counts are found, and $Q_x = (E_{\text{lo}} - E_{\text{lo}})/(E_{\text{up}} - E_{\text{lo}})$ is defined to be the normalized quartile. The ratio of the bottom-to-top quartile ($x = 25$ and 75, respectively) is representative of a two-point slope of the spectrum. For the case of a single temperature, the median, $m(= Q_{50})$, is a function of the absorption. The quartiles are not independent, as the absorption changes the quartile ratio for a given temperature. Hong et al. (2004) plot the data by normalizing the quartile ratio axis as $3(Q_{75}/Q_{25})$, while the median is compressed as $\log[m/(1 - m)]$.

On such a plot one can distinguish changes in temperature from extinction and can even distinguish thermal and nonthermal changes.

To determine whether cluster members occupy a common region in such a quartile diagram, we study the most probable cluster members, those sources that lie within 200$''$ of IRS 2. By calculating the number of X-ray sources within 1$'$ of each X-ray source, we find that the distribution of X-ray sources is sharply peaked with a full width at half-maximum of about 200$''$. Plotting all such X-ray sources in the diagram shown in Figure 3 (left) shows that there is a clustering of the data in color space. Figure 3 (right) shows the same axes but now for sources more than 200$''$ off-axis. The difference is striking. Of the 63 sources with over 100 counts and less than 200$''$ off-axis, 62 lie in the range $-0.65 < \log \left[ \frac{m}{1 - m} \right] < 0.25$. The vertical line in Figure 3 shows $\log \left[ \frac{m}{1 - m} \right] = -0.65$. We fitted the distribution of the data between those two points using a two-variable linear regression first-order equation, $3(Q_{75}/Q_{25}) = 1.2 \log[m/(1 - m)] + 1.8$, with a mean absolute deviation (MAD; Beers et al. 1990) of 0.15. The diagonal lines in Figure 3 are three deviations above and below this fit. Sixty-one of the bright sources near the cluster center could be found within three deviations of the fit. One point was clearly not a cluster member (source 39), and the other point was on the fringe. This is indicative of a group of sources with similar extinctions and spectral signatures.

There are 209 X-ray sources within 200$''$ of IRS 2 and with less than 100 counts. Of these, 36 have between 50 and 100 counts and all lie within three MAD of the best-fit line. An additional 54 have between 30 and 50 counts. Two of these (source 34 and source 175) are clearly too unabsorbed (too low a value in the $X$-axis) to be considered cluster members. Three others lie just below the $-3 \sigma$ deviation demarcation, but we do not exclude these as candidate members, since the measurement errors can account for this small difference. The remaining 119 sources have less than 30 counts; four of these are discrepant by having too low a value along the $X$-axis, and we exclude these sources from cluster membership. Fifteen lie just below the $-3 \sigma$ deviation demarcation. This is more than twice the rate of such sources seen with 30–50 counts. Again, we do not exclude these sources; we instead conclude that the measurement errors associated with the quartiles is biased such that sources with low counts have systematically lower values of $Q_{75}/Q_{25}$ and that the errors are twice as high for sources with less than 30 counts compared to those with 30–50 counts. This last point is consistent with the results from Hong et al. (2004). Overall, we exclude seven X-ray sources within 200$''$ of IRS 2 from cluster membership based on the quartile analysis. We consider the 202 remaining X-ray sources to be probable cluster members.

There are 183 X-ray sources more than 200$''$ from IRS 2. Of these, 110 lie within the $\pm 3 \sigma$ deviation limits described above. We chose these limits to be somewhat inclusive and to err on the side of membership. We exclude from probable cluster membership 94 sources that are outside of these limits and more than 200$''$ from IRS 2. Along with the seven sources nearer to IRS 2, the identification of 101 sources in the field as background (or foreground) field objects is consistent with expectations derived from the ChaMPlane survey (Hong et al. 2005). Our observations reached a mean flux limit of about $2 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$ ($2-10 \text{ keV}$) averaged across the field. Preliminary results from the ChaMPlane survey for Chandra fields in the plane of the Galaxy away from the Galactic core indicate that we can expect to
find about 70 background active galactic nuclei (AGNs), cataclysmic variables, neutron stars, black holes, and other non-pre-main-sequence (PMS) star point sources in the ACIS-I field. Some examples include sources 14, 18, and 113, which are quite hard and absorbed in X-rays and yet appear unabsorbed at NIR wavelengths (see §6). The ChaMPlane effort excludes soft X-ray sources such as dMe stars and white dwarfs and thus should be taken as a lower limit.

The probable cluster members are noted in Table 2. Probable nonmembers are noted in Table 3. In these tables the first column gives the source number, followed by the quartile values, \(Q_{25}, m,\) and \(Q_{75},\) with errors interleaved. The plot values are calculated for convenience and listed in the last two columns.

### 3.1. Cluster Density

We plot the positions of the members and nonmembers in Figure 4. It is clear that the members are clustered, while the nonmembers have a more uniform distribution. A density analysis was performed by calculating the number of cluster members within 15" of each cluster member. Asymmetries in a plot cluster density as a function of the distance from the dominant ionizing source IRS 2 indicate that it is not the center of the cluster. The geometric centroid was calculated in terms of stellar (X-ray source) density, not mass density, using cluster members within 100" of IRS 2 and is located at 08h50m04s64, -47\(^\circ\)30\'44"00. This is displaced 10''4 to the west-southwest of IRS 2 and aligned roughly with the 10 \(\mu\text{m} dust ridge reported by Smith et al. (1999). Varying the inclusion radius by 50'' can change this centroid location by 6''; this is mostly controlled by the initial guess that the center was near IRS 2.

The results of the full density analysis are shown in Figure 5. The cluster density drops to half the peak density of about 100 X-ray sources per arcminute at about 15" (~0.12 pc) from the cluster center. We find that the cluster is very sharply peaked, with broad wings relative to a Gaussian profile; hence, this is not a relaxed system. We fit the data in Figure 5 as an exponential of the number of sources per square parsec, \(\sim \exp(-5.0d),\) where \(d\) is the distance from the cluster center in parsecs. The peak cluster density, as measured via this fit, is about 400 \(\pm 20\) X-ray sources per square parsec (~100 \(\pm 10\) X-ray sources per square parsec.

### Table 2

| Source No. | \(Q_{25}\) | \(Q_{25\text{err}}\) | \(m\) | \(M_{\text{err}}\) | \(Q_{75}\) | \(Q_{75\text{err}}\) | \(\log[m/(1-m)]\) | \(3(Q_{25}/Q_{75})\) |
|------------|-----------|-----------------|-----|-------------|-----------|-----------------|------------------|----------------|
| 4          | 0.15      | 0.01            | 0.23| 0.02        | 0.33      | 0.04            | -0.53            | 1.32            |
| 8          | 0.18      | 0.01            | 0.29| 0.03        | 0.45      | 0.03            | -0.39            | 1.17            |
| 11         | 0.27      | 0.05            | 0.41| 0.03        | 0.57      | 0.05            | -0.16            | 1.41            |
| 16         | 0.19      | 0.02            | 0.31| 0.03        | 0.47      | 0.09            | -0.35            | 1.24            |
| 19         | 0.17      | 0.01            | 0.26| 0.06        | 0.57      | 0.06            | -0.46            | 0.90            |
| 21         | 0.16      | 0.01            | 0.22| 0.01        | 0.39      | 0.02            | -0.55            | 1.19            |
| 22         | 0.31      | 0.03            | 0.45| 0.06        | 0.71      | 0.13            | -0.08            | 1.31            |
| 23         | 0.14      | 0.01            | 0.22| 0.01        | 0.34      | 0.03            | -0.56            | 1.20            |
| 24         | 0.19      | 0.03            | 0.28| 0.06        | 0.56      | 0.09            | -0.42            | 1.03            |
| 25         | 0.19      | 0.03            | 0.32| 0.04        | 0.53      | 0.14            | -0.33            | 1.10            |
| 26         | 0.21      | 0.05            | 0.32| 0.05        | 0.56      | 0.18            | -0.33            | 1.12            |
| 27         | 0.22      | 0.03            | 0.32| 0.04        | 0.45      | 0.16            | -0.34            | 1.48            |
| 28         | 0.42      | 0.04            | 0.57| 0.04        | 0.80      | 0.05            | 0.12             | 1.57            |
| 30         | 0.15      | 0.01            | 0.23| 0.03        | 0.41      | 0.03            | -0.52            | 1.11            |
| 31         | 0.22      | 0.01            | 0.31| 0.03        | 0.47      | 0.04            | -0.36            | 1.43            |

### Table 3

| Source No. | \(Q_{25}\) | \(Q_{25\text{err}}\) | \(m\) | \(M_{\text{err}}\) | \(Q_{75}\) | \(Q_{75\text{err}}\) | \(\log[m/(1-m)]\) | \(3(Q_{25}/Q_{75})\) |
|------------|-----------|-----------------|-----|-------------|-----------|-----------------|------------------|----------------|
| 1          | 0.11      | 0.01            | 0.16| 0.02        | 0.44      | 0.14            | -0.74            | 0.74            |
| 2          | 0.20      | 0.02            | 0.37| 0.08        | 0.95      | 0.13            | -0.23            | 0.62            |
| 3          | 0.19      | 0.01            | 0.29| 0.04        | 0.60      | 0.11            | -0.39            | 0.95            |
| 5          | 0.19      | 0.03            | 0.41| 0.09        | 0.68      | 0.19            | -0.15            | 0.85            |
| 6          | 0.11      | 0.01            | 0.16| 0.03        | 0.35      | 0.14            | -0.71            | 0.92            |
| 7          | 0.31      | 0.06            | 0.68| 0.08        | 1.16      | 0.13            | 0.32             | 0.80            |
| 9          | 0.20      | 0.03            | 0.34| 0.1        | 1.10      | 0.21            | -0.28            | 0.53            |
| 10         | 0.20      | 0.03            | 0.37| 0.05        | 0.71      | 0.28            | -0.24            | 0.84            |
| 12         | 0.27      | 0.04            | 0.41| 0.08        | 0.94      | 0.23            | -0.16            | 0.85            |
| 13         | 0.14      | 0.02            | 0.27| 0.06        | 0.60      | 0.20            | -0.43            | 0.72            |
| 14         | 0.31      | 0.05            | 0.45| 0.05        | 0.78      | 0.23            | -0.08            | 1.18            |
| 15         | 0.09      | 0.02            | 0.13| 0.10        | 0.60      | 0.40            | -0.82            | 0.44            |
| 17         | 0.09      | 0.01            | 0.11| 0.03        | 0.25      | 0.34            | -0.91            | 1.08            |
| 18         | 0.17      | 0.03            | 0.39| 0.08        | 0.67      | 0.21            | -0.20            | 0.77            |
| 20         | 0.31      | 0.06            | 0.47| 0.08        | 0.93      | 0.16            | -0.06            | 0.99            |

Note.—Table 2 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
arcminute). The density of the nonmembers is $2.3 \pm 1.1 \text{ arcmin}^{-2}$.

A plot of the density profile of these sources shows a slight enhancement about 100$''$ from the cluster centroid, indicating that as many as eight of the candidate nonmembers have been misidentified as such. While the quartile system as applied here is not a perfect system for determining cluster membership based on X-ray colors, it appears highly effective.

We can use these data to estimate the total cluster size. Recent work on mass stratification in the ONC by Feigelson et al. (2005) indicates that, at our sensitivity limit of $\log L_X \sim 30.0$, one detects about 16% of the stars in a cluster that is similar to the ONC. Comparisons to measurements of the ONC are quite appropriate to RCW 38, as both clusters have mid- to early-O stars. Since our sensitivity was a little below this limit, we expect that we are detecting at most 15% of the cluster members. This should include half of all stars above 0.5 $M_\odot$. Scaling from the 360 members detected, we estimate that the total cluster size could be as high as 2400 members, with a peak density of about 1000 sources in the central square parsec.

4. VARIABILITY

In this section we examine the variability of the X-ray source population. Variability studies allow us to begin to assess the plausibility of X-ray generation mechanisms. These can be constrained by the timescales and flux changes observed in the variability. Variability also offers corroborating evidence that a source is stellar in nature and hence a possible cluster member. Unlike other X-ray sources, almost all coronal sources vary given a long enough observation (see Getman et al. 2005). These variations can either be stochastic or impulsive deviations from constancy.

Various methods can be employed to investigate variability. This topic has been reviewed briefly by Wolk et al. (2005) and more thoroughly by Güdel (2004) and Favata & Micela (2003). One rigorous technique commonly used is a one-sample Kolmogorov-Smirnov (K-S) test to identify whether the photon arrival times are consistent with a constant rate. The K-S test does not give any information on the nature of the variability in objects. We identify X-ray sources as variable if they have a K-S statistic less than...
0.001. That is, the cumulative event arrival time distribution deviates from a linear distribution at a confidence greater than 99.9%. Among the brightest 31 sources (those with over 200 net counts), 7 (23%) were variable at >99.9% confidence. That rate is maintained among the 80 sources with over 100 net counts, of which 19 (23%) were variable at >99.9% confidence.

4.1. Flaring

About 25% of the bright sources are detected as variable in 100 ks, but the K-S test tells us nothing about flaring. As demonstrated in Wolk et al. (2005), the use of Bayesian blocks (BBs; Scargle 1998) provides a method of flare detection without the biases inherent in binning the data. In some senses the BB method is similar to the K-S test; the existence of more than one block indicates that the flux has changed at a certain confidence level. However, while the K-S test reports very little about the nature of the change, the number of BBs and measurements of the mean rate, σ, and duration of those blocks allow quantitative analysis. The BB method is explicitly designed to avoid binning the observation into equally spaced time intervals. BBs conform to complex X-ray light curves remarkably well (see Getman et al. 2005). We tested each light curve with a “prior ratios” set to approximate both 95% and 99% confidence that a flux change has occurred.

Using the BB technique, 7 of the 31 sources (22.5%) with over 200 counts and 21 of the brightest 80 (26%) could not be fitted with one block at a constant level with over 99% confidence. This number is very similar to the 23% that varied at similar confidence as measured by the K-S test. Overall, 37 sources required more than one BB. These results are tabulated as part of Table 1.

The BB method converts the light curve to temporal periods of constant flux; thus, one can measure the amount of rise between the blocks and estimate the rate of change between blocks. In their study of the extremely deep COUP data set, Wolk et al. (2005) indicated that the flux has changed at a certain confidence level.

4.2. Flare Rates

We can use these data to assess flare rates. Since the fraction of stars seen to vary (via either the BBs or the K-S method) does not decrease as we limit the total counts from 200 to 100, we assume that the test is fully valid at this count rate. There are 103 stars with over 75 counts, of which 23 vary (30%). This fraction exceeds the variability rate seen at higher fluxes, so we do not appear to be missing any true variable. However, of 48 sources with between 50 and 75 counts, only 5 (10%) vary. Of the 87 sources with between 30 and 50 counts, 7 (8%) vary. Clearly, there is a roll-off in the sensitivity to variability below 75 counts. To prevent biases in the data we constrain the following analysis to sources with over 100 counts.

Nine of 72 (12.5%) probable cluster members with over 100 counts flared in 96.7 ks. This represents a little less than half of the bright cluster members that are detected as variables. Nonmember source 404 flared; none of the six other bright nonmembers varied. Assuming that all stars are the same and that there are no stars more prone to flare than others, we conclude that there are about 775 ks between flares. This is between the values obtained for solar mass stars in the ONC (one flare per 640 ks; Wolk et al. 2005) and all stars in the much older cluster NGC 2516 (about 1 Ms−1; Wolk et al. 2004).

Finally, variability analysis can be used to assess the veracity of the quartile approach to cluster member selection. We expect stars to vary more than other X-ray sources. Of the 35 stars seen to vary with 99% confidence, 34 of them are identified as cluster members by the quartile approach. This gives us great confidence among the bright sources. Furthermore, variability was detected on sources down to 30 counts. In the field there are 202 cluster members with between 30 and 100 counts, and 16.8% of those vary. In contrast, only one of the 22 non–cluster members varies. The lone nonmember to flare was source 404. From spectral analysis we find that it is one of the most unobscured sources in the field and hence likely a foreground dMe star.

5. SPECTRAL ANALYSIS

Analysis of the X-ray spectra of each source was performed to determine the bulk temperature of the corona and the intervening column of hydrogen. Source and background pulse height distributions in the total band (0.3–8.0 keV) were constructed for each X-ray source. Model fitting of spectra was performed using Sherpa (Freeman et al. 2001). The final fits were done with CIAO version 3.1.0.1. The CIAO script psextract was used to extract source spectra and to create an ancillary response function and redistribution matrix function files. For sources with over 30 counts, data for each source were grouped into energy bins that required a minimum of 8 counts per bin and background-subtracted. The Levenberg-Marquardt optimization method and χ2-Gehrels statistics were employed. For sources with under 30 counts, models were fitted unbinned using CSTAT statistics (Cash 1979) and Powell optimization.

5.1. Choosing a Spectral Fitting Model

For uniformity, it is desirable to settle on a single model spectrum for all sources. To find the most appropriate model for our sources, we ran a series of test fits on the brightest 80 sources, those with over 100 counts. In these tests, the 80 sources were successively fitted with various absorbed thermal plasma models. These included the model from Raymond & Smith (1977), the MEKAL model (Mewe et al. 1985, 1986; Kaastra 1992; Liedahl et al. 1995), APEC,3 thermal bremsstrahlung (Kellogg et al. 1975), and blackbody and single power-law models. The fitting was done using Sherpa, and the absorption law was assumed to be \( \text{abs}(E) = e^{-N_H \sigma(E)} \), in which the photoelectric absorption cross sections \( \sigma(E) \) are taken from Morris & McCammon (1983). Absorption and temperature or the power-law index (\( \Gamma \)) were left as fitted parameters. A two-temperature absorbed Raymond-Smith model was also tested. To evaluate the results

3 An emission spectrum from collisionally ionized diffuse gas calculated using the APEC code, ver. 1.10. More information can be found at http://hea-www.harvard.edu/APEC.

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of the test, we used an outlier-resistant determination of the mean and standard deviation of the reduced $\chi^2$ to each fit on a model-by-model basis. The mean was calculated after trimming away outliers more than two MADs from the median (similar results were obtained with a three-MAD cut). The results are summarized in Table 4. In this table the columns represent the various models: Raymond-Smith plasma, two-temperature Raymond-Smith plasma, APEC, MEKAL, thermal bremsstrahlung, blackbody, and power law. The rows represent the mean $\chi^2$ per degree of freedom (dof), the MAD, and the number of outlying measurements rejected in the MAD determination process. This last row indicates the stability of the model relative to the data. From the data in the table it is clear that the blackbody and power-law fits are poor for the bulk of the sources. Among the single-temperature fits, the Raymond-Smith and APEC fits are clearly superior to MEKAL and thermal bremsstrahlung for these data. The reduced $\chi^2$ tends to be slightly higher for both thermal bremsstrahlung and MEKAL, and the fraction of rejected fits is very high for the MEKAL models.

It was difficult to determine superiority between the APEC and Raymond-Smith models. APEC had a slightly lower mean $\chi^2$ per dof but more scatter than Raymond-Smith fits. APEC performed marginally better for the brightest sources, but Raymond-Smith performed better at the faint end. We compared luminosities determined by the two models and found that the standard deviation between the two models was about 20%. This difference is
Fig. 7.—Flares on fainter sources. Shown are light curves of 14 X-ray sources with flares and <100 total counts. The sources are 11, 28, 37, 46, 66, 211, 250, 292, 345, 353, 362, 380, 445, and 453.
Fig. 8.—Light curves of the 10 X-ray sources seen to vary at 99.9% confidence and that did not flare based on the criteria given in Wolk et al. (2005). All of these sources are probable cluster members. Source 289 is the only source in the cluster to show four distinct flux levels at 99.9% confidence.

### TABLE 4

Summary Model Fit Data

| Model      | R-S   | Two-Temp. R-S | APEC | MEKAL | Thermal Brem. | Blackbody | Power Law |
|------------|-------|---------------|------|-------|----------------|-----------|-----------|
| Mean       | 0.41  | 0.44          | 0.41 | 0.45  | 0.44           | 1.44      | 1.23      |
| MAD        | 0.017 | 0.019         | 0.016| 0.020 | 0.019          | 0.090     | 0.069     |
| No. Rejected | 14   | 9             | 19   | 32    | 16             | 16        | 11        |
dominated by outliers; removing the 10 outliers lowered the deviation between the two models to 3%. When we compared the \( N_{\text{H}} \) to the outliers to the visual extinction (calculated in § 6) we found that the \( N_{\text{H}} \) calculated using the Raymond-Smith model was more consistent with the independently derived \( A_V \) and the independently derived \( N_{\text{H}} \)-to-\( A_V \) relation. For these reasons we chose the Raymond-Smith model for our main spectral-fitting model.

A few sources are fitted very well by a single power law; these are probably background AGNs. Still, in most cases a thermal model (e.g., APEC or Raymond-Smith) is better even for non–cluster members. Similarly, some very cool sources, probably white dwarfs, are best fitted as blackbodies (see § 7.2). Finally, some sources simply defy fitting by any one model.

### 5.2. Global Fitting of X-Ray Spectra

When performing bulk processing on the catalog of \( \approx 460 \) X-ray sources we found that it was advantageous to perform a preliminary fit to the data with a simple blackbody and use the result of this fit as the initial guess for the Raymond-Smith fit. This ensured that the local minimum found by Levenberg-Marquardt optimization was realistic. From the experiments above, we see that the two-temperature models were no better than the one-temperature fits. This is expected in a high-extinction environment, as we have here. Any cool component that may exist is overwhelmed by soft absorption due to the large hydrogen column. We attempted detailed two-temperature fits for all sources with over 100 counts. Of the 80 fits, only 35 of them had more than 10% of the flux contributed by each component and had temperatures of the two components separated by more than 5%. Two issues show up throughout the fitting process: (1) There is a fundamental degeneracy in the fits between \( N_{\text{H}} \) and \( kT \); fits of similar quality can be obtained by increasing \( N_{\text{H}} \) and then correspondingly changing the temperature. This is especially true in regions of high absorption, such as RCW 38. (2) Since there is little sensitivity to X-rays above 10 keV, model fits are not very reliable much above this energy range. Because of this, if the fitted temperatures exceed 15 keV, we simply label them “>15” in the tables.

The fit results for the two-temperature fits are tabulated in Table 5, including results for three non–cluster members. In Table 5, column (1) gives the source name from Table 1; column (2) gives the goodness of fit to an absorbed two-temperature Raymond-Smith plasma model. The results of the fits to X-ray sources we found that it was advantageous to perform a one-temperature fit using a two-step fitting procedure. Initial conditions were set so that \( N_{\text{H}} = 1.0 \times 10^{21} \) cm\(^{-2} \) and \( kT = 1.0 \) keV. Then an initial fit was made with an absorbed thermal blackbody model. These fit results were then used as initial conditions for an absorbed Raymond-Smith plasma model. The results of the fits to the Raymond-Smith models are tabulated in Table 6. In Table 6,
column (1) gives the source name from Table 1, and column (2) gives the goodness of fit to an absorbed one-temperature Raymond-Smith plasma in terms of $\chi^2$ per dof. Columns (3)–(7) give the fit parameters $N_H$ and $kT$ and their associated errors and unabsorbed flux. The luminosity of each source is calculated based on the derived unabsorbed flux and the cluster distance of 1.7 kpc and listed in column (8). The median $N_H$ of these stars is $2.6 \times 10^{22}$ cm$^{-2}$, while the median $kT$ is $\sim$2.55 keV.

We separately tabulated fits for sources with less than 30 counts. CSTAT statistics and Powell optimization were used, appropriate for faint sources. These fits have large, although nonsystematic, errors (Table 7). The columns in this table are identical to the columns of Table 6. The median $N_H$ of these stars is $3.2 \times 10^{22}$ cm$^{-2}$, while the median $kT$ is $\sim$2.1 keV. Note that a change to higher $N_H$ would lead to a high $kT$ as well if the sources were similar. It is easy to understand that the fainter sources are preferentially more absorbed, but it appears that they are also cooler.

Finally, we performed fits on the non–cluster members. Only 29 of these have over 30 counts. They were fitted as two-temperature plasmas, although the fits to sources 39 and 447 will be revisited later. Most of the 26 remaining sources were well fitted by the Raymond-Smith model with reduced $\chi^2$ $< 1.71$ for all 26 and reduced $\chi^2$ between 1.3 and 0.3 for all but three. The median $kT$ for these sources was about 1.25 keV, and

### Table 6

Cluster Members Fit with One-Temperature Spectra

| Source No. | $\chi^2$ per dof | $N_H$ ($10^{22}$ cm$^{-2}$) | $N_{H\text{eff}}$ ($10^{22}$ cm$^{-2}$) | $kT$ (keV) | $kT_{err}$ (keV) | Unabsorbed Flux (log ergs cm$^{-2}$ s$^{-1}$) | $L_X$ (log ergs s$^{-1}$) |
|------------|------------------|-------------------------------|---------------------------------------|-------------|------------------|------------------------------------------|--------------------------|
| 3............. | 0.23             | 3.19                          | 1.06                                  | 1.04        | 0.46             | $-13.08$                                 | 31.45                    |
| 4............. | 0.36             | 1.22                          | 0.63                                  | 1.72        | ...              | $-13.42$                                 | 31.11                    |
| 11............ | 0.41             | 3.54                          | 0.63                                  | 3.72        | ...              | $-13.43$                                 | 31.11                    |
| 14............ | 0.17             | 4.80                          | 1.79                                  | 3.51        | 1.16             | $-13.60$                                 | 30.94                    |
| 16............ | 0.19             | 2.22                          | 1.37                                  | 2.08        | 1.59             | $-13.69$                                 | 30.85                    |
| 19............ | 1.01             | 2.48                          | 1.14                                  | 0.73        | 0.40             | $-13.28$                                 | 31.26                    |
| 21............ | 0.48             | 0.90                          | 0.16                                  | 3.87        | 1.09             | $-13.17$                                 | 31.36                    |
| 22............ | 0.32             | 4.46                          | 1.04                                  | 3.67        | ...              | $-13.54$                                 | 30.99                    |
| 24............ | 0.14             | 1.71                          | 0.73                                  | 2.83        | 1.55             | $-13.91$                                 | 30.63                    |
| 25............ | 0.23             | 2.20                          | ...                                   | 2.06        | ...              | $-13.67$                                 | 30.87                    |
| 28............ | 0.38             | 14.04                         | 5.99                                  | 6.14        | 4.52             | $-13.08$                                 | 31.46                    |
| 30............ | 0.24             | 0.95                          | 0.28                                  | 3.01        | 0.06             | $-13.69$                                 | 30.85                    |
| 31............ | 0.26             | 3.64                          | 0.69                                  | 1.54        | 0.27             | $-13.10$                                 | 31.44                    |
| 33............ | 0.19             | 1.31                          | 0.42                                  | 2.56        | 0.94             | $-13.76$                                 | 30.78                    |
| 35............ | 0.67             | 2.97                          | ...                                   | 1.41        | ...              | $-13.50$                                 | 31.04                    |
| 37............ | 0.14             | 2.28                          | 0.79                                  | 1.97        | 0.72             | $-13.75$                                 | 30.78                    |
| 40............ | 0.30             | 1.28                          | 0.44                                  | 1.48        | 0.40             | $-13.84$                                 | 30.70                    |
| 46............ | 0.20             | 9.17                          | 2.96                                  | 2.15        | 0.54             | $-13.03$                                 | 31.51                    |
| 50............ | 0.32             | 4.77                          | 1.40                                  | 1.17        | 0.28             | $-13.09$                                 | 31.45                    |

Note.—Table 6 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

### Table 7

Faint Cluster Members Fit with One-Temperature Spectra

| Source No. | $\chi^2$ per dof | $N_H$ ($10^{22}$ cm$^{-2}$) | $N_{H\text{eff}}$ ($10^{22}$ cm$^{-2}$) | $kT$ (keV) | $kT_{err}$ (keV) | Unabsorbed Flux (log ergs cm$^{-2}$ s$^{-1}$) | $L_X$ (log ergs s$^{-1}$) |
|------------|------------------|-------------------------------|---------------------------------------|-------------|------------------|------------------------------------------|--------------------------|
| 26............. | 0.26             | 3.39                          | 0.94                                  | 2.06        | 0.63             | $-13.84$                                 | 30.00                    |
| 27............. | 0.26             | 8.80                          | 1.12                                  | 0.46        | 0.05             | $-11.64$                                 | 29.88                    |
| 38............. | 0.27             | 1.39                          | 0.57                                  | $>15$       | ...              | $-13.98$                                 | 30.39                    |
| 41............. | 0.22             | 16.87                         | 3.19                                  | 0.87        | 0.12             | $-12.22$                                 | 29.98                    |
| 43............. | 0.31             | 2.03                          | 0.55                                  | 3.01        | 1.05             | $-13.85$                                 | 30.20                    |
| 45............. | 0.24             | 2.12                          | 0.73                                  | 4.70        | 1.99             | $-13.96$                                 | 30.21                    |
| 47............. | 0.27             | 7.15                          | 1.74                                  | 2.09        | 0.49             | $-13.41$                                 | 30.21                    |
| 48............. | 0.30             | 0.85                          | 0.29                                  | 1.88        | 0.59             | $-14.07$                                 | 29.98                    |
| 49............. | 0.24             | 7.94                          | 2.55                                  | 1.98        | 0.60             | $-13.67$                                 | 29.91                    |
| 52............. | 0.21             | 7.23                          | 2.62                                  | 2.92        | 0.94             | $-13.67$                                 | 30.15                    |
| 58............. | 0.32             | 2.88                          | 0.44                                  | 0.71        | 0.17             | $-13.62$                                 | 29.48                    |
| 60............. | 0.23             | 2.72                          | 0.88                                  | 2.50        | 0.94             | $-14.02$                                 | 29.93                    |
| 63............. | 0.26             | 1.69                          | 0.48                                  | 1.39        | 0.40             | $-13.93$                                 | 29.86                    |
| 65............. | 0.24             | 2.96                          | 1.02                                  | 7.82        | ...              | $-13.92$                                 | 30.28                    |
| 68............. | 0.17             | 3.86                          | 0.62                                  | 0.60        | 0.09             | $-12.80$                                 | 29.74                    |
| 75............. | 0.22             | 9.52                          | 2.18                                  | 0.96        | 0.17             | $-12.89$                                 | 29.82                    |

Note.—Table 7 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.
the mean $N_H$ was about $0.5 \times 10^{21} \text{ cm}^{-2}$. As a group, they are cooler and less absorbed than the cluster members. For completeness we tabulated fits for non–cluster members with under 30 counts. These results are tabulated in Tables 8 and 9. The columns in these tables are identical to the first seven columns of Table 6. Thermal spectra of the brighter non–cluster members range from 140 eV to over 15 keV. The softer sources may be foreground dMe stars or white dwarfs (see § 7). In Table 9 the temperatures of 30% of the sources exceed 15 keV (compared to 7.5% in Table 7), indicating these are probably power-law sources and most likely background AGNs.

We summarize all the spectral data in Figures 9, 10, and 11, which show the histograms of the derived plasma temperature, source extinction, and X-ray luminosity function (XLF), respectively. Focusing first on the cluster member sources with 30 counts or greater, the typical plasma temperature is similar to that of stars in the ONC (Getman et al. 2005). We derive a mean (rejecting outliers)\textsuperscript{4}

\textsuperscript{4} Since the mean temperature is about 2 or 3 keV and the total fit range is 0–50 keV, the outlying values are very nonsymmetric. A high outlier can have a value more than 45 keV above the mean, while a low outlier is within 3 keV of the mean. Hence, we reject 5 \sigma outliers (high and low) before calculating the final mean.

### Table 8

| Source No. | $\chi^2$ per dof | $N_H$ ($10^{22}$ cm$^{-2}$) | $N_{H,\text{err}}$ | $kT$ (keV) | $kT_{\text{err}}$ | Unabsorbed Flux (log ergs cm$^{-2}$ s$^{-1}$) |
|-----------|------------------|---------------------------|-----------------|------------|----------------|-----------------------------------|
| 1         | 0.54             | 1.24                      | 0.42            | 0.34       | 0.08           | $-13.00$                          |
| 2         | 0.14             | 2.43                      | ...             | 1.82       | ...            | $-13.70$                          |
| 6         | 0.20             | 1.00                      | 0.39            | 0.72       | 0.29           | $-13.57$                          |
| 13        | 0.34             | 0.46                      | 0.34            | 4.60       | 0.15           | $-14.22$                          |
| 32        | 0.02             | 0.26                      | 0.37            | 4.28       | 0.13           | $-14.41$                          |
| 34        | 0.12             | 0.00                      | 0.17            | 0.30       | ...            | $-14.46$                          |
| 54        | 0.06             | 0.01                      | ...             | 1.04       | ...            | $-14.32$                          |
| 61        | 0.21             | 4.82                      | 0.66            | 3.31       | ...            | $-13.72$                          |
| 64        | 0.18             | 0.53                      | 0.48            | 0.76       | 0.44           | $-14.19$                          |
| 69        | 0.53             | 0.60                      | 0.15            | 0.37       | 0.07           | $-13.11$                          |
| 80        | 0.35             | 0.51                      | ...             | 0.82       | ...            | $-14.17$                          |
| 113       | 0.50             | 0.56                      | 0.43            | 2.46       | 1.17           | $-14.09$                          |
| 175       | 0.16             | 0.64                      | 0.37            | 0.90       | 0.27           | $-14.10$                          |
| 214       | 0.37             | 0.86                      | 0.11            | 4.38       | 0.76           | $-13.17$                          |
| 245       | 0.09             | 1.02                      | ...             | 1.76       | ...            | $-14.01$                          |
| 277       | 0.16             | 0.16                      | ...             | 0.91       | ...            | $-14.50$                          |
| 286       | 0.30             | 0.40                      | ...             | 0.60       | ...            | $-14.21$                          |
| 399       | 0.34             | 1.25                      | 0.03            | 1.89       | ...            | $-14.22$                          |
| 446       | 0.37             | 0.49                      | 0.25            | 1.00       | 0.19           | $-13.63$                          |
| 447       | 0.40             | 1.18                      | 0.12            | 0.29       | 0.04           | $-11.95$                          |
| 452       | 0.24             | 0.75                      | 0.21            | 0.14       | 0.03           | $-12.30$                          |
| 454       | 0.22             | 1.84                      | 0.62            | 0.64       | 0.27           | $-13.37$                          |

### Table 9

| Source No. | $\chi^2$ per dof | $N_H$ ($10^{22}$ cm$^{-2}$) | $N_{H,\text{err}}$ | $kT$ (keV) | $kT_{\text{err}}$ | Unabsorbed Flux (log ergs cm$^{-2}$ s$^{-1}$) |
|-----------|------------------|---------------------------|-----------------|------------|----------------|-----------------------------------|
| 5         | 0.37             | 0.27                      | ...             | >15        | ...            | $-14.15$                          |
| 7         | 0.40             | 3.26                      | 1.27            | >15        | ...            | $-13.82$                          |
| 9         | 0.33             | 6.69                      | 0.85            | 0.39       | 0.03           | $-11.72$                          |
| 10        | 0.35             | 3.32                      | 0.64            | 1.27       | 0.27           | $-13.44$                          |
| 12        | 0.33             | 2.97                      | 0.97            | 2.80       | 1.06           | $-13.85$                          |
| 14        | 0.35             | 3.64                      | 1.12            | 3.71       | 1.28           | $-13.67$                          |
| 15        | 0.25             | 0.63                      | 0.15            | 0.34       | 0.06           | $-13.87$                          |
| 17        | 0.25             | 1.28                      | 0.14            | 0.17       | 0.02           | $-12.02$                          |
| 18        | 0.35             | 0.79                      | 0.34            | 5.47       | 2.95           | $-14.13$                          |
| 20        | 0.38             | 2.43                      | 1.02            | >15        | ...            | $-13.90$                          |
| 29        | 0.22             | 0.56                      | 0.34            | 4.95       | ...            | $-14.46$                          |
| 36        | 0.31             | 4.95                      | 1.34            | 1.58       | 0.42           | $-13.56$                          |
| 42        | 0.21             | 0.80                      | 0.15            | 0.49       | 0.09           | $-13.81$                          |
| 44        | 0.27             | 0.68                      | 0.44            | >15        | ...            | $-14.29$                          |
| 51        | 0.26             | 1.18                      | 0.60            | 9.55       | ...            | $-14.33$                          |
| 61        | 0.28             | 2.47                      | 0.91            | >15        | ...            | $-13.90$                          |
| 74        | 0.28             | 1.55                      | 0.48            | 3.05       | 1.21           | $-13.98$                          |

Note.—Table 9 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
plasma temperature of 2.9 keV (MAD = 0.15). The bulk of the sources are between 1 and 4 keV with a tail-off to higher temperatures. The \( N_H \) column is symmetrically distributed among the sources with an outlier-resistant mean of 2.8 \( \times 10^{22} \) cm\(^{-2} \) and a MAD of 0.10. If we include the fainter members, we find that these tend to be more absorbed with \( N_H \) = 4.3 \( \times 10^{22} \) cm\(^{-2} \) and a little cooler with \( (kT) \approx 2.0 \) keV.

In Figure 11 we plot both the observed XLF and the nominal “complete” XLF of the ONC, which was parameterized by Feigelson et al. (2005) as a lognormal distribution with \( \langle \log L_X \rangle \approx 29.3 \) and \( \sigma \pm 1.0 \). We normalized the lognormal distribution to fit the RCW 38 bins with \( \log L_X > 31.0 \). The RCW 38 XLF becomes incomplete around \( \log L_X \approx 30.75 \) and is essentially cut off near \( \log L_X \approx 30.0 \). For the case of RCW 38 at 1.7 kpc with a mean \( N_H = 22.4 \), the estimated point source sensitivity limit is \( \log L_X \approx 30.1 \), consistent with the empirical result from Feigelson et al. (2005).

5.3. Diffuse Emission

Wolk et al. (2002) reported the detection of extensive and bright diffuse emission throughout RCW 38. In light of the estimate of over 1000 undetected cluster members, it is worthwhile to briefly revisit here whether the diffuse emission may be simply those undetected sources. We find this explanation for the diffuse emission unlikely for several reasons. First, one can attempt to count up the missing photons in Figure 11 by assigning the mean number of missing counts in the first incomplete bin to be 4 (this number is chosen because sources as faint as 5 counts on-axis are generally detected, but it is clearly an overestimate, since the mean value will be lower than the maximum) and then summing the counts from each bin. The result is about 1000 counts, which is significantly less than the 6200 counts detected in the diffuse emission. Second, the region of emission extends about 2.0 (1 pc) in the southeast-northwest direction and about 3.0 (1.5 pc) in the northeast-southwest direction (see Fig. 2 of Wolk et al. 2002). Ninety percent of the cluster members are within 1 of the cluster center, and there are essentially no members outside of 2. Third, the spectrum of the diffuse emission outside of the cluster center is very hard, with temperatures greater than 10 keV if fitted as a
thermal spectrum and more accurately fitted as a power law. This is not the result of the sum of thermal spectra. It is likely that flux from unresolved point sources in the core contributes significantly to the emission detected there and may account for the thermal nature of the diffuse emission measured in the core. But stars cannot account for the diffuse emission more than 0.15 pc (∼15") from the cluster center.

6. INFRARED PROPERTIES OF X-RAY SOURCES

Since the RCW 38 region is optically obscured, there is little optical data on the X-ray sources. The region has been explored in the NIR, however. A search of the Two Micron All Sky Survey (2MASS) point source catalog returns about 2500 sources in the X-ray field. About 500 of these have photometric errors of <5% in all three bands. However, there are only 16 such 2MASS sources in the central 2.5 × 2.5. This is because most sources are embedded in extended emission and cannot be properly measured by 2MASS with its 2" nominal resolution. Because of this, the central region of RCW 38 was observed by the Very Large Telescope (VLT) in 1998 November as part of the first-light observations on VLT UT1 (Moorwood et al. 1998). Data in the J, H, and Ks bands were obtained using the ISAAC imager with exposure times of 320, 320, and 210 s, respectively (Fig. 12). The field measures 2.5 × 2.5 and was reduced to colors and magnitudes using the standard apphot and photcal packages in IRAF.6 There were 447 sources detected in all three filter bands. Minimum photometric errors reached 5% at J, H, and Ks magnitudes of 17.6, 18, and 17.1, respectively. The errors were dominated by variability in the nebular background. The 5σ level detections had measured magnitudes of 19.8, 19.0, and 18.0 in the J, H, and Ks filters, respectively.

There were 36 sources detected in one or two of the VLT filters, but not all three. This usually occurred when the source was highly obscured and no H- and/or J-band detection was made. If there was an X-ray source coincident with one of these objects, we estimated magnitudes in the filters in which they were detected by calculating the mean conversion from instrumental magnitude to the standard scale for the 447 sources that had good IR colors and applying this linear factor to the observed instrumental magnitude. The resulting magnitude estimates had errors of about 20%, since no color term could be applied. We performed astrometry on this image by matching against 10 X-ray sources spread around the field using the WCSTools program imwcs (Mink 2002), which automatically finds stars in an image, matches them to stars in a reference catalog, and computes the relation between sky coordinates and image coordinates. Typical offsets were <0.3. Direct comparison of 2MASS and VLT positions for sources near the edge of the VLT field showed similar offsets, although 1σ offsets were seen in some cases. We then matched all the X-ray sources in the central region to this VLT catalog. For VLT sources, our matching procedure was to match to the nearest source, rejecting all matches with offsets <1". The median offset is 0.45. Outside the central pointing we matched sources against the 2MASS catalog. The maximum offset between X-ray and 2MASS IR positions allowed in matching was

6 IRAF is the Image Reduction and Analysis Facility, a general-purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatory (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

### TABLE 10

| Source No. | IR ID        | Offset | J  | Jdiff | H   | Hdiff | K   | Kdiff | A_V | Model | Flags |
|------------|--------------|--------|----|-------|-----|-------|-----|-------|-----|-------|-------|
| 4          | 2MASS 085829.85–472823.0 | 0.11   | 14.058 | 0.028 | 12.895 | 0.026 | 12.429 | 0.019 | 5.16 | GK star | AAA   |
| 8          | 2MASS 085834.64–472816.4 | 0.30   | 14.968 | 0.032 | 13.312 | 0.02  | 12.314 | 0.019 | 10.32 | M star | AAA   |
| 14         | 2MASS 085828.04–472628.3 | 1.29   | 15.459 | 0.047 | 14.406 | 0.054 | 13.98  | 0.064 | 4.4   | Bright | AAA   |
| 16         | 2MASS 085826.58–473156.7 | 0.91   | 14.599 | 0.033 | 13.602 | 0.046 | 13.12  | 0.036 | 2.74  | Bright | AAA   |
| 19         | 2MASS 085851.51–472934.3 | 0.40   | 16.556 | 0.161 | 14.881 | 0.062 | 14.049 | 0.068 | 11.14 | Bright | CAA   |
| 21         | 2MASS 085843.88–472856.9 | 0.22   | 12.572 | 0.023 | 11.529 | 0.027 | 10.76  | 0.023 | 5.35  | M star  | AAA    |
| 22         | 2MASS 085844.19–473441.4 | 1.44   | 17.086 | 0.08  | 15.336 | 0.113 | 13.536 | 0.067 | ...   | ...    | ...    |
| 23         | 2MASS 085844.40–473253.3 | 0.26   | 14.64  | 0.042 | 13.299 | 0.03  | 12.658 | 0.035 | 6.22  | Disk    | AAA    |
| 24         | 2MASS 085844.53–473406.5 | 0.57   | 16.619 | 0.165 | 14.394 | 0.048 | 13.295 | 0.042 | 14.77 | GK star | CAA    |
| 26         | 2MASS 085846.69–473055.7 | 0.43   | 16.357 | 0.085 | 15.065 | 0.085 | 13.843 | 0.063 | ...   | ...    | UAA    |
| 27         | 2MASS 085847.18–473151.3 | 0.38   | 18.017 | 0.015 | 15.759 | 0.149 | 14.791 | 0.126 | ...   | ...    | UBB    |
| 28         | 2MASS 085847.53–473322.9 | 1.38   | 16.381 | 0.085 | 15.673 | 0.133 | 14.687 | 0.122 | ...   | ...    | UBB    |
| 30         | 2MASS 085847.70–472817.4 | 0.97   | 13.966 | 0.09  | 15.087 | 0.09  | 14.443 | 0.11  | ...   | ...    | UAB    |
| 31         | 2MASS 085848.63–473221.4 | 0.05   | 16.987 | 0.23  | 14.336 | 0.047 | 13.106 | 0.044 | ...   | ...    | DAA    |

Note: Table 10 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
1.5. This added error budget was due to the fact that 2MASS was used primarily for sources away from the Chandra aim point; hence, there is larger positional uncertainty in these Chandra sources. The 2MASS colors and magnitudes have typical errors of less than 20% at magnitudes of about 17, 16, and 15, respectively, with errors of about 5% for sources that are 1 mag brighter than these limits.

NIR matches were found for 349 of the X-ray sources listed in Table 1. Of the 360 cluster members, 294 have NIR matches; these are listed in Table 10. Column (1) of this table gives the X-ray source number. Column (2) gives the 2MASS name or a VLT name, depending on which data are used. Column (3) lists the offset between the X-ray and IR positions. Columns (4)–(9) list the $J$, $H$, and $K$-band observations and errors.
A reddening vector indicative of AV sequence, and the dashed line running parallel to the reddening vector and the dot-dashed line is the CTTS locus (after Lada & Adams 1992 and Meyer et al. 1997). Ks Column (10) indicates the such a young cluster. 2003), this is still a very small disk fraction for X-ray sources in 3. The color-color diagrams for the cluster members and non-members to those with errors in x 36 of these; none have NIR excesses that require a disk. That do not appear to be cluster members. We determine extinctions to 36 of these; none have NIR excesses that require a disk.

There are 55 matches to the 81 nonmembers as determined in § 3. The color-color diagrams for the cluster members and non-members are shown in Figure 13. In these plots we restrict the sources to those with errors in J and Ks of <0.2 mag and high-light sources with errors of less than 0.05 mag. Most nonmember sources appear to be unobscured blackbodies, although two are obscured by AV ~ 10. Among the cluster members, none appear to be normal unobscured photospheres. Most of the X-ray sources that are candidate cluster members appear quite obscured. Twenty-six of the 184 (14%) IR sources with errors of <20% lie within the classical T Tauri star (CTTS) region of the color-color diagram as described by Meyer et al. (1997). If we restrict ourselves to the 104 X-ray members with <5% errors, 9 stars lie in the disk region. While H - Ks is not very sensitive to disk excess (Lada & Lada 2003), this is still a very small disk fraction for X-ray sources in such a young cluster.

If the IR data are of high enough quality (error < 0.2) they allow a tentative extinction estimate. We simply calculate the amount of reddening required to move the object from zero reddening to the observed location. The zero-reddening location is different for a star with and without a disk and varies depending on spectral type for pure photospheres. To calculate the extinction we first assume the least obscured case, that all the stars have disks, and deredden the photometric colors until they intersect the CTTS locus. This is the only possible solution for stars outside the pure reddening box (Lada & Adams 1992). For stars inside the box, two-disk solutions exist where the extinction correction crosses the main sequence. One of these solutions roughly corresponds to the star being an M star, the other with the photosphere being warmer. We measure the extinction for stars inside the box for each hypothesis (disk, M star, and HM star). Thus, we determine up to three possible extinctions for each star. For stars that lie either below the CTTS locus or to the left of the main sequence, no estimate of extinction is possible. In addition, there are stars outside the reddening box due to observational errors, not disks. If the dereddened star is within 2 σ of the reddening box on the low-mass side of the main sequence (high H - K), we calculate the M star reddening. We do not calculate the reddening of the HM star hypothesis, because the angle between the zero-age main sequence (ZAMS) and the extinction curve is very shallow, leading to large errors. If the dereddened star is outside the reddening box on the high-mass side, falling near the elbow of the main sequence in the color-color diagram, then no additional reddening is possible beyond the disk/M star hypothesis, which yields the same result. We label these “GK stars” in the table, since this is their inferred spectral type on the main sequence.

The IR extinction of stars that are bright X-ray sources can be cross-checked against the NiH column derived from spectral fits to the X-ray data. To start this process we used the relation of NiH to AV recently derived for Chandra ACIS-I data by Vuong et al. (2003) of NiH = AV (1.6 × 10^{21}) cm^{-2} and found which model hypothesis (disk, M star, or HM star) minimizes the difference in the AV estimates. The hypothesis that most closely matched the measured NiH absorption column was chosen as the probable source extinction in Table 10. In about half the cases the difference between the IR-detected AV and the AV inferred from NiH was <1 mag. However, in about 20% of cases the difference was greater than 5 mag. This large scatter led to some concern about the appropriateness of the NiH-to-AV relation that was used. The mean difference between AV calculated using the infrared extinction correction method and AV calculated using the Vuong relation is 2.62 mag (MAD = 0.35).

To assess and refine the formulation of the NiH-to-AV relation, we fitted the extinction, as determined above, to the measured NiH values. We restricted the fit to 31 bright X-ray and IR objects with a magnitude error of less than 5% in J and an uncertainty of less than 30% in NiH. Using a regression fit that rejected outliers, we found a relation of NiH = AV (1.7 × 10^{21}) cm^{-2}. Forcing zero extinction at zero column of NiH, we get a best fit of NiH = AV (2.0 × 10^{21}) cm^{-2}, which is shown in Figure 14. These are intermediate to results derived using ROSAT data (Ryter 1996) and
those of Vuong et al. (2003). Using \( N_H = A_V (2.0 \times 10^{21}) \text{ cm}^{-2} \), the mean difference between \( A_V \) calculated using the infrared extinction correction method and \( A_V \) calculated using the \( N_H \) relation drops to 0.28 mag. The MAD of this fit is 0.29, consistent with no offset.

At this point we revisited the choices we made among the three extinction possibilities of each star to verify that the selection made when we assumed \( N_H = A_V (1.6 \times 10^{21}) \text{ cm}^{-2} \) was still the best fit to the updated \( N_H \)-to-\( A_V \) relation. We found that in all cases, the extinction as derived using the infrared method was insensitive to the choice of \( N_H \)-to-\( A_V \) conversion, despite the fact that the conversion was used for vetting the models. This was because the differences in the possible NIR extinction hypothesis were more significant than the modest 20% difference between the \( N_H \)-to-\( A_V \) relations.

The extinction to 160 X-ray-selected cluster members was determined via infrared photometry. Sixteen of these stars have \( K \)-band excesses indicative of disks based on their infrared colors. Most of the remainder have multiple viable extinction solutions. Using the X-ray absorption as a guide, 33 of these are most consistent with disks for a total of 49 (31%). Thirty-five appear to be obscured M stars without \( K \)-band disk signatures, while 49 appear near the “elbow” of the main sequence and, while no disk is in evidence, there is little that can be determined about the photosphere either. The remaining 28 stars have colors too blue to be K or M stars or have optically thick disks at the \( K_s \) band.

We create an intrinsic \( K \)-band luminosity function (KLF) by correcting the observed \( K \)-band magnitude for extinction by \( A_K = 0.109 A_V \) (Bessell & Brett 1988). In Figure 15 we find that the KLF is peaked at \( K_s = 12 \). At a distance modulus of 11.15, this is an absolute \( K \) magnitude of about 0.85. Masses are estimated using the theoretical isochrones of Siess et al. (2000; SDF) with metallicity of 0.02, no convective overshooting, and a cluster age of 0.5 Myr.\(^7\) Metallicity was varied from 0.03 to 0.01 with only a 3% effect on the \( K_s \)-band magnitude at 2.7 \( M_\odot \). The error induced by the age estimates, which range between 0.5 and 1.0 Myr, was almost 50%. At an assumed age of 0.5 Myr a star with an absolute \( K \) magnitude of 0.85 has a mass range of about 1.05 \( M_\odot \). Completeness appears to become an issue at \( K_s \approx 13 \), which corresponds to 0.5 \( M_\odot \). The ratio of non-X-ray stars per magnitude with corrected \( K \) magnitudes between 10 and 12 and those with corrected \( K \) magnitudes between 13 and 14 is about 1 : 4. The same ratio for the X-ray-detected sources is about 1 : 2. Thus, we detect about 50% of the stars at an extinction-corrected \( K_s \approx 13 \) (0.5 \( M_\odot \)). This is consistent with the prediction given in \(^3 \) 3.1. We have 50 detections at 14 mag in \( K_s \). These sources have masses ranging from 0.25 \( M_\odot \) down to the brown dwarf limit.

6.1. Other IR Sources in the VLT Field

Examination of the VLT non-X-ray-detected sources can be used to analyze the completeness of the X-ray data. Since the VLT image is centered near the core of a very dense cluster with a dense molecular cloud behind it, we expect the stellar sources in the VLT field to be dominated by the cluster members. Using the galactic models of Wainscoat et al. (1992), we expect minimal contamination, perhaps six sources brighter than \( K_s = 17 \) in this small FOV. None of the 129 X-ray sources in the VLT FOV has been excluded as a cluster member based on its X-ray properties.

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\(^7\) All manner of evolutionary tracks are estimates, and concerns about accuracy of the estimates become larger at younger ages (see Hillenbrand & White 2004 for a full discussion). Initially, the age is estimated as 0.5 Myr based on the degree of embeddedness of the sources, but we expect a range of ages as seen in the ONC. We use the Siess et al. tracks because of their large mass coverage, especially at high masses.
There are a total of 482 stars in the VLT field with good colors in $J$, $H$, and $K_s$. Of these, 129 are X-ray sources. We assume that the bulk of the remaining 353 are cluster members; their properties are listed in Table 12. We note that about 25% of the IR sources were detected in the X-ray observation (after a small correction for VLT sources detected in less than three bands). This is somewhat at odds with the prediction of a 16% detection rate based on ONC data (e.g., X-ray spectra or mid-IR photometry) it cannot be determined whether the hot part of the inner disks. Without additional data (e.g., X-ray spectra or mid-IR photometry) it cannot be determined which of the other 51% have disks.

by crosses and non-X-ray sources by open circles. We find that about 10 of the 482 stars are too faint and unobscured to be cluster members. Thus, there is some contamination by non–cluster members in the VLT data set. If we take the 16% detection fraction as a minimum fraction of cluster members detected in X-rays and 25% as the maximum, then the total cluster membership is between 1400 and 2400.

In Figure 16 it appears the X-ray sample is not uniform compared with the non-X-ray sample. The X-ray sample seems more sensitive to very embedded high-mass sources and less sensitive to embedded lower mass sources. The 353 VLT sources not detected in X-rays are indicated in the color-color diagram shown in Figure 17. The minimum extinction to each star was derived using the same procedure as in § 6. In the non-X-ray group, 173 stars (49%) needed to be modeled as stars with disks. This fraction is much higher than the 14% disk fraction among the X-ray sources. Furthermore, the 49% disk fraction is a lower limit. The remainder of the stars may or may not have disks, as the NIR is only sensitive to the hot part of the inner disks. Without additional data (e.g., X-ray spectra or mid-IR photometry) it cannot be determined which of the other 51% have disks.

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**TABLE 12**

IR Photometry in the VLT Field (Non-X-Ray Sources)

| IR ID     | R.A. (J2000.0) | Decl. (J2000.0) | $J$  | $J_{\text{err}}$ | $H$  | $H_{\text{err}}$ | $K$  | $K_{\text{err}}$ | $A_V$ Min. |
|-----------|----------------|----------------|-----|-----------------|-----|-----------------|-----|-----------------|------------|
| VLT 085911.02—472949.8................. 08 59 11.022 | –47 29 49.81 | 19.537 | 0.148 | 17.724 | 0.048 | 16.190 | 0.038 | 5.58 |
| VLT 085910.86—473101.6................. 08 59 10.867 | –47 31 01.67 | 16.763 | 0.033 | 16.097 | 0.020 | 15.586 | 0.023 | 0.00 |
| VLT 085910.79—473028.9................. 08 59 10.795 | –47 30 28.94 | 18.031 | 0.068 | 16.531 | 0.025 | 14.550 | 0.015 | 0.00 |
| VLT 085910.72—473110.4................. 08 59 10.720 | –47 31 10.40 | 19.667 | 0.149 | 17.745 | 0.046 | 16.176 | 0.034 | 6.81 |
| VLT 085910.59—472945.7................. 08 59 10.596 | –47 29 45.70 | 18.288 | 0.068 | 16.753 | 0.027 | 15.356 | 0.021 | 2.84 |
| VLT 085910.40—472933.7................. 08 59 10.405 | –47 29 33.72 | 16.673 | 0.087 | 17.420 | 0.038 | 16.060 | 0.032 | 0.00 |
| VLT 085910.38—472942.6................. 08 59 10.385 | –47 29 42.61 | 17.808 | 0.054 | 15.600 | 0.016 | 13.753 | 0.010 | 8.54 |
| VLT 085910.08—473133.8................. 08 59 10.088 | –47 31 33.87 | 17.889 | 0.056 | 16.588 | 0.025 | 15.528 | 0.023 | 2.30 |
| VLT 085910.07—473130.3................. 08 59 10.073 | –47 31 30.35 | 18.173 | 0.068 | 16.885 | 0.031 | 15.652 | 0.026 | 0.74 |
| VLT 085910.00—472951.5................. 08 59 10.004 | –47 29 51.50 | 18.399 | 0.075 | 16.508 | 0.024 | 15.135 | 0.019 | 7.95 |
| VLT 085909.95—473124.4................. 08 59 09.955 | –47 31 24.40 | 18.770 | 0.092 | 17.486 | 0.040 | 16.420 | 0.095 | 4.94 |
| VLT 085909.67—473105.1................. 08 59 09.672 | –47 31 05.16 | 19.403 | 0.174 | 17.753 | 0.066 | 16.420 | 0.095 | 4.94 |
| VLT 085909.67—473117.5................. 08 59 09.672 | –47 31 17.57 | 18.613 | 0.082 | 17.455 | 0.039 | 16.167 | 0.031 | 0.00 |
| VLT 085909.64—473114.9................. 08 59 09.647 | –47 31 14.91 | 19.296 | 0.121 | 17.196 | 0.034 | 15.597 | 0.025 | 9.03 |
| VLT 085909.36—472938.8................. 08 59 09.368 | –47 29 38.80 | 17.672 | 0.052 | 16.507 | 0.024 | 15.457 | 0.023 | 0.50 |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 12 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

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**Fig. 16.**—Infrared color-magnitude diagram for all sources in the VLT field. X-ray sources are indicated by crosses, and non-X-ray sources are indicated by open circles. The 0.5 Myr (squares), 1.0 Myr (triangles), and ZAMS (filled circles) isochrones for 2.5—0.08 $M_{\odot}$ are plotted (Siess et al. 2000). Visual extinction of 30 mag for a 2.5 $M_{\odot}$ star is indicated by the dashed line. The dot-dashed lines indicate extinction of 30 mag for 0.08 $M_{\odot}$ stars at ages of 0.5 (upper) and 1.0 Myr (lower).

**Fig. 17.**—Infrared color-color diagram ($J - H$ vs. $H - K$) for VLT sources without X-ray counterparts in the RCW 38 Chandra field. Symbols are the same as in Fig. 13.
This indicates that the X-ray sample is biased away from stars with inner disks. There are two possible, nonexclusive explanations for this. First, the disk itself will absorb X-rays. Second, the X-ray production mechanism for stars with disks may be different and lower in luminosity than it is for PMS stars without disks. These possibilities are discussed further by Preibisch et al. (2005). The intrinsic $K_s$-band luminosity is not the primary difference between the X-ray-detected and non-X-ray-detected populations. Of the 129 VLT stars detected in X-rays, 8 are fainter than $K = 16$ and 2 are fainter than $K = 18$. Out of the remaining 353 VLT-detected sources, 36 are fainter than $K = 16$ and 1 is fainter than $K = 18$. The ratios are statistically indistinguishable. The KLF of the non-X-ray-detected sources (Fig. 15, right) shows a shape similar to that of the KLF of the X-ray-detected members. Finally, a two-sided K-S test comparing the colors of the brightest 100 X-ray- and non-X-ray-detected sources found a 4% probability that they were drawn from the same population. Even when all sources were included, the K-S test found a 1% chance that they were drawn from the same source population. We conclude that the X-ray sample, while not complete and certainly biased against disks, is not particularly mass-biased down to the substellar limit. Only one X-ray source is detected significantly below the nominal brown dwarf limit: source 281 at 07′68′′ from VLT 085907.79–473122.2, a very likely cluster member since its extinction is about 5.25 $A_v$.

6.2. Possible O and B Stars

Using the extinction-corrected KLF we performed a survey of the cluster for O and B star candidates. On the ZAMS a star of 2.7 $M_\odot$ is a late B star. On the SDF mass tracks at 0.5 Myr a 2.7 $M_\odot$ star has an absolute $K_s$-band luminosity of $-0.35$, as calculated using the online SDF model isochrones as discussed in § 6. We chose an age of 0.5 Myr and solar metallicity ($Z = 0.02$). To convert the effective temperatures resulting from the models to colors, we used the conversion table from Kenyon & Hartmann (1995). Both mass and luminosity were derived from the models using the extinction-corrected $K_s$ magnitude of the X-ray-selected members as estimated earlier in this section and the distance modulus of 11.15.

This use of the SDF isochrones leads to the identification of 31 X-ray sources as candidate OB stars. One star (source 390) was excluded, since it had no measurable extinction and hence is probably foreground. Another, source 435, is also excluded because it is both a very faint X-ray source and somewhat softer than the rest of the group. Including source 221/IRS 2, which has been discussed elsewhere as an ~O5 star (Smith et al. 1999; Wolk et al. 2002), and source 251, which is a very absorbed and luminous X-ray source, there are 29 X-ray-detected candidate OB stars.

There are two additional stars in the VLT field that, while not detected in X-rays, are still identified as O or B star candidates based on their extinction-corrected luminosity. VLT 085905.44–473045.2 (VLT 232) is in the wings of several X-ray sources that could easily obscure X-ray emission from this source, up to about 30 counts. This would provide a perfectly reasonable log ($L_X/L_{bol}$) of $-5.89$. It is somewhat surprising that VLT 085906.96–473023.2 (VLT 453) is not an X-ray source if it is indeed a B star. While it is in the vicinity of source 251, it is 3″ away, and the background contamination is only about 0.5 counts. If this is a B star it is a very weak X-ray source, perhaps due to an unusually weak wind.

Figure 18 shows the location of the 31 OB star candidates. In Table 13 we list the OB stars in RCW 38. Columns (1)–(4) of the table list the source ID, right ascension, declination, and distance from the cluster center, respectively. Columns (5) and (6) list the magnitudes of visual extinction as derived from the IR (col. [5]) and X-ray (col. [6]) methods. The absolute $K_s$ magnitude derived from the measured $K_s$ magnitude, the distance modulus, and the infrared extinction is given in column (7). In general, the infrared extinction is lower than the estimate derived from the $N_H$ column. This occurs for stars fitted with the disk model, since we stop the dereddening process when we reach a model consistent with a late-type star with a disk. For the most part the agreement between the extinction measurements (IR-derived and X-ray-derived) is very good, leaving less than 0.3 mag of variation in the derived absolute $K_s$ magnitude. This contributes about a 25% uncertainty to the mass estimate. This is usually in the sense of a mass underestimate. Columns (8) and (9) list the bolometric luminosity (derived from the age and absolute $K_s$ magnitude and $V_L$.

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8 Source 390 had less than 30 X-ray counts; hence, its identification as a cluster member was already on questionable footing.
the relative X-ray luminosity \( \log (L_X/L_{bol}) \)). The latter values are consistent with known O and B stars.

The distribution of the OB candidates mimics the roughly symmetrical and peaked distribution of the cluster as a whole. Twenty-one of the candidates are within 111″ of the cluster centroid. Four candidates lie more than 300″ from the cluster centroid. The most distant candidates tend to have extreme values of \( L_X/L_{bol} \), indicating that they may not be at the distance of RCW 38. The finding of \( \sim 31 \) candidate OB stars is consistent with our estimate for the overall membership cluster as about 1.7 times that of the ONC. The ONC has about 15 O and B stars (Stelzer et al. 2005). Although 31 OB stars is a little on the high side, this large number of candidates may indicate that the four off-axis candidates may not be cluster members. We assume the cluster is 1 Myr instead of 0.5 Myr, the cutoff for O and B stars would become more than 0.5 mag fainter \( \log (L_X/L_{bol}) \rangle \) and would bring the total population of O and B stars in the cluster over 60, which we consider unlikely.

7. SPECIFIC INTERESTING SOURCES

For the analysis presented here, the primary utility of X-ray emission in young stars is as a tracer of youth and to measure the gas and dust along the line of sight. The former is especially useful, since other, more obvious tracers of youth, such as NIR emission, fade more quickly with age than X-ray emission. However, several of the X-ray sources, both cluster members and non–cluster members, are interesting for their X-ray characteristics. In our data set we found two remarkably cool objects, several sources with very hot plasma, and others that were extremely embedded. We discuss them and the brightest 10 μm source below.

7.1. Very Bright IR Sources

RCW 38 was identified as a star-forming region through the presence of several bright infrared sources. IRS 2 (Frogel & Persson 1974) is clearly the revealed central O star. As we discussed previously (Wolk et al. 2002), this is coincident with the brightest X-ray source in the field, source 221. The X-ray count rate is 0.062 counts s\(^{-1}\), so the pile-up fraction is very small. The X-ray spectrum was not well fitted by any single-component thermal model. Our best fit was to a two-temperature Raymond-Smith plasma dominated by a cool component at 0.77 keV and a warm component at 2.5 keV. These temperatures are very consistent with those of strong wind sources in the ONC (Stelzer et al. 2005). Strong wind X-ray sources were modeled by Stelzer et al. to have a hydrodynamic wind with many small shocks. IRS 2 has an X-ray luminosity 10% greater than that of \( \theta \) Orionis C. While this star was too bright to be measured in the VLT observations, good 2MASS data are available and demonstrate that...
IRS 2 is about 5–10 times more luminous than θ1 Orionis C at the K band.

IRS 1, the brightest 10 μm source (Frogel & Persson 1974), appears not to be a point source at all. Rather, it is a complex region to the west of IRS 2. Mid-infrared 10 and 20 μm observations by Smith et al. (1999) find that IRS 1 is a dust ridge with a number of peaks, including one at the location of IRS 1 and others noted by the letters A–D in Figure 1 of Smith et al. They propose that the region can be explained in terms of a windblown cavity, where the stellar wind from the hot young star IRS 2 has cleared a cavity about itself, and the ridge of emission near IRS 1 represents the material that has been swept up into the shell around IRS 2. M. C. Vigil et al. (2006, in preparation) find that there is a peak in the centimeter continuum emission within this ridge. They conclude that the density enhancement could lead to future star formation.

The dust enhancements identified as regions A, B, and E by Smith et al. are associated with X-ray emission sources 187, 197, and 174, respectively. Source 187 is among the fainter sources with only 18 counts; the absolute magnitude near 13, B–K = 1.9, and a proper motion of −0.88 mas yr−1. This is consistent with the star lying near the G, K, and early M stars portion of the color–color diagram with little reddening (less than 0.03 mag at V). Furthermore, this source hasTycho B and V magnitudes of 10.93 and 10.87, respectively, and a proper motion of 47.1 ± 2.5 mas yr−1 (Høg et al. 2000). The colors are consistent with an unabsorbed K3–4 main-sequence star (Koornneef 1983) within 100 pc. The X-ray source is most likely an unseen degenerate companion.

Source 174 (0859°03′67″, −47°30′40″) is the strongest X-ray source in the IRS 1 region. This source is well matched to the westernmost star in a triplet located on the NIR dust ridge that is clearly visible in the center of Figure 2. The IR counterpart to source 174 is highly reddened with a K magnitude near 13, H–Ks ~ 1.7, and no J detection. The visual extinction inferred from the N_H column is about 17. From this we infer a mass of about 2.0 M_☉. The best fit to the X-ray spectrum is a fairly hot 5.1 keV plasma. The high temperature may be indicative of very long (perhaps tens of stellar radii), low-density, magnetic structures in this object, supporting the idea that IRS 1 is in a region of ongoing star formation. Any soft X-ray component would be absorbed, so we cannot comment on whether there is a bright soft component to the X-ray emission here.

7.2. Cool Objects

Sources 39 and 447 are both very cool and bright. Both exceed 300 counts with almost all the emission below 2.0 keV. They are the only two sources in the data set that are well fitted by blackbodies. Figure 19 shows the detailed blackbody fits. Both fits have null probabilities in excess of 0.95. The N_H columns fitted to the sources are 6.0 and 7.5 × 10^21 cm^−2, respectively; thus, we conclude that they are foreground objects. The derived blackbody temperatures are 100 and 150 eV, consistent with the emission expected from the surface of a neutron star or, more likely, a white dwarf. Neither shows evidence of variability.

Both are associated with bright 2MASS sources. Source 39 is 0.′1 offset from 2MASS 085850.39−473319.5 with K = 8.9, J − H = 0.44, and H − K = 0.15. This is consistent with the star lying near the G, K, and early M stars portion of the color–color diagram with little reddening (less than 0.03 mag at V). Furthermore, this source has Tycho B and V magnitudes of 11.93 and 11.40, respectively, and a proper motion of 47.1 ± 2.5 mas yr−1 (Høg et al. 2000). The colors are consistent with an unabsorbed K3–4 main-sequence star (Koornneef 1983) within 100 pc. The X-ray source is most likely an unseen degenerate companion.

Source 447 is 0.′35 offset from 2MASS 085956.09−473304.3, which has K = 8.1, J − H = 0.33, and H − K = 0.18, colors that are consistent with a late K-type star. However, the source is also coincident with LS 1223, with V = 11.48, B − V = 0.86, and U − V = −0.19, consistent with a moderately reddened [E(B−V) = 0.4] early B star. This extinction is not consistent with the measured N_H column or the IR extinction, which are A_V of 3.75 and 3.0, respectively. Furthermore, the derived V − Ks of 3.4 is consistent with an unobscured K4–K5 star. To obtain consistent colors we need to model source 447 as a K4 star with a young white dwarf companion (which may account for the blue excess) at about 50 pc.
Fig. 20.—Spectra of the hottest, most embedded sources in our sample. Source 56 (a) is fitted with a 14.7 keV thermal plasma with $N_{\text{H}}/C_{\text{24}}$: $9 \times 10^{22}$ cm$^{-2}$. Source 147 (b) is fitted with a 11.0 keV thermal plasma with $N_{\text{H}}/C_{\text{24}}$: $7 \times 10^{22}$ cm$^{-2}$. Source 251 (c) is fitted with a 10.7 keV thermal plasma with $N_{\text{H}}/C_{\text{24}}$: $3 \times 10^{23}$ cm$^{-2}$. Source 149 (d) is fitted with a 9.6 keV thermal plasma with $N_{\text{H}}/C_{\text{24}}$: $8 \times 10^{22}$ cm$^{-2}$. Source 108 (e) is fitted with a 8.9 keV thermal plasma with $N_{\text{H}}/C_{\text{24}}$: $5.37 \times 10^{22}$ cm$^{-2}$. Source 118 (f) is fitted with a 3.7 keV thermal plasma but a large $N_{\text{H}} > 10^{33}$ cm$^{-2}$. All sources have a reduced $\chi^2 < 0.6$, except for source 251, which has a reduced $\chi^2 \sim 0.95$. Residuals to the fits are shown beneath each fit.
7.3. Very Hot Objects

At the other end of the spectrum there are five bright sources that were best fitted by a single temperature plasma with a temperature exceeding 100 MK ($kT > 8.6$ keV) and in excess of 100 counts, so we have good confidence in the fits. Such stars are interesting because the underlying physics required to generate these high temperatures is probably quite different from the physics required to generate the roughly 2.5 keV characteristic plasma seen around most million-year-old stars. At a minimum, such temperatures probably require magnetic structures exceeding a stellar radius (Favata et al. 2005). Furthermore, the physics required to sustain such plasmas for the entire observing window is probably not related to the loop reconnection seen in flares. We discuss the sources in order of descending temperature. Two of the five stars flared during the observation; for these stars the high temperatures are at least partially related to the flare episodes. The other three sources showed no evidence of strong flares. The spectra of all five are shown in Figure 20.

Source 56: This source, with about 309 counts, is fitted with the hottest plasma in the field. The fit with a 14.7 keV thermal plasma with $N_{\text{H}} = 3.9 \times 10^{22}$ cm$^{-2}$ is very good, with a reduced $\chi^2$ of $<0.5$. It is not in our VLT field and has neither a 2MASS nor a Mosaic Space Experiment counterpart, so it could be an AGN or other exotic object. Fits with a power law yield a slightly poorer fit, with reduced $\chi^2$ of 0.33 but perfectly reasonable values of $N_{\text{H}} = (4.05 \pm 0.07) \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.83 \pm 0.21$, indicating that it could be powered by synchrotron electrons. However, it is 166$''$ from the cluster center, which puts it on the edge of the cluster core. While it is possible that this is a chance superposition of a background object, its location and count rate make a protostellar hypothesis more likely.

Source 147: This source, with almost 200 counts, is best fitted with an 11.0 keV thermal plasma with $N_{\text{H}} = 1.7 \times 10^{22}$ cm$^{-2}$ with a reduced $\chi^2$ of $<0.6$. Fits to a power law yield a poorer fit, with reduced $\chi^2$ of $\sim 0.45$ and reasonable values of $N_{\text{H}} = 0.9 \times 10^{22}$ cm$^{-2}$ and $\Gamma = 1.07$, but the residuals are systematic, indicating that the power-law model expects too much flux at the hard end. Furthermore, since it is only 50$''$ from the cluster center, it is within the VLT FOV. Indeed, it is quite bright in the NIR, with $K = 11.5$ and an $A_K \sim 10$ consistent with the $N_{\text{H}}$ measurement. The absolute magnitude of $-0.65$ at the 1.7 kpc distance of RCW 38 is consistent with a 3.5 $M_\odot$ star near the birth line (Palla & Stahler 1993). The mass of this star could be significantly higher due to the nonmonotonic relation between $K$ magnitude and mass in this regime.

Source 251: This source, with over 280 counts, is the closest to the cluster center among this group, $<22''$ off-axis. It is the only one of the five hottest sources coincident with the molecular ring discussed by M. C. Vigil et al. (2006, in preparation). It lies on the inner edge of the molecular and dust rings. It is fitted with a 10.7 keV thermal plasma with a very high column, $N_{\text{H}} = 2.3 \times 10^{23}$ cm$^{-2}$, with a reduced $\chi^2$ of 0.95. Fits to a power law yield a negative slope, and forcing a positive slope yields reduced $\chi^2$ of $>9$. Since the star is highly embedded, it is not detected at the $J$-band. Our $K_s$-band detection is 14.9 with $H - K_s$ of 1.5. Based on the $N_{\text{H}}$ column we estimate $A_K$ to be about 12.5. This yields an absolute $K$ magnitude of $-8.75$. This corresponds to about 25,000 $L_\odot$, which is similar to that of the Becklin-Neugebauer object (Becklin & Neugebauer 1967) and consistent with an O star of greater than 10 $M_\odot$. This star has a clear flare, and about 80% of the observed flux from the star is associated with that flare.

Source 149: This is a 300 count source 95$''$ off-axis. It is outside of the VLT field but coincident with the very red 2MASS 085902.07–473209.4 (0.3$''$ offset). The observed $K$ magnitude is 13.2 with $H - K_s < 1.2$ (the $H$ value is an upper limit). It is well fitted to a 9.6 keV thermal plasma with a very high column, $N_{\text{H}} = 3.8 \times 10^{22}$ cm$^{-2}$, with a reduced $\chi^2$ of 0.4. The equivalent $A_K$ is about 2.1, which gives an absolute $K$ magnitude of about 0. About 50% of the flux from this star emanated during a flare. This flare would have to be extremely hot, ~150 MK, to interpret this as a normal T Tauri star with a flare.

Source 108: This source is located just southwest of source 149, 132$''$ off-axis. Its X-ray spectrum is very similar to nearby...
sources 147 and 149, $kT = 8.9$, $N_H = 5.37 \times 10^{22} \text{ cm}^{-2}$, with a reduced $\chi^2$ of 0.4. There is no NIR detection at this location in the 2MASS database, nor would we expect any if the source is similar to sources 149 and 147 given the additional extinction present.

These stars are all interpreted as O or B stars, which should, in principle, have strong, optically thick winds. However, in the sample of eight such stars in the ONC by Stelzer et al. (2005), only two sources needed thermal plasma in excess of 3.33 keV to fit the data. In both cases the hot component was a fit artifact listed as “$kT > 15 \text{ keV}$”; in one case the hot component was less than 10% of the X-ray flux, and in the other case it was $< 1\%$. We do not believe there is evidence for a strong optically thick wind giving rise to such temperatures. The rate of flaring, two out of five in 100 ks, is also inconsistent with a collisional wind model. This leads us to conclude that these are good candidates for objects undergoing extremely high rates of accretion.

We note that sources 251, 147, 149, and 108 lie on a nearly straight line running from northeast to southwest. This line is parallel to the dust extension seen in the millimeter observation reported by M. C. Vigil et al. (2006, in preparation) and the axis of the diffuse plasma emission reported by Wolk et al. (2002). Source 251 lies near the northern extent of the peak plasma emission (Fig. 21). There is an additional cluster member associated with very hot plasma and over 50 counts, source 345, which also lies close to this line. Source 345 is unusual among the hot sources because it is a fairly low-extinction $N_H = 7.5 \times 10^{21} \text{ cm}^{-2}$ and corresponds to a fairly bright ($K = 13.46$) 2MASS source. This is the luminosity expected from a 1.5 $M_\odot$ star at about 0.5 Myr.

In addition to source 251, there is only one bright source with a measured column with $N_H > 10^{23} \text{ cm}^{-2}$: source 118. This appears to be a normal PMS star with a hot component of about 3.7 keV and a cool component of about 0.9 keV. The spectrum is well fitted with a two-temperature Raymond-Smith plasma with a reduced $\chi^2$ of about 0.25. From the fit we derive a very high X-ray luminosity $L_X = 32.9$. The source is marginally detected by the VLT in the $K$ band, giving it a $K$-band magnitude of $< 18.6$. Three other sources with over 50 counts were found to be absorbed by columns with $N_H > 10^{22} \text{ cm}^{-2}$: sources 28, 78, and 322. These sources all lie along the same line as the stars with very hot plasma (Fig. 21). Perhaps this is a filament of gas and dust behind the currently active region of star formation.

8. SUMMARY

We observed the massive, embedded young cluster RCW 38 and the surrounding region using the Chandra X-Ray Observatory and in the NIR using the VLT. Here we summarize our results:

1. We detected 460 X-ray point sources in the field. The limiting luminosity for sources in the cluster is about $L_X \sim 30.0$. We detect over half of all stars down to 0.5 $M_\odot$. Some of the detections appear to be $< 0.1 M_\odot$.

2. Using quartile analysis we identified 360 of the X-ray sources as cluster members. Since this approach is unusual, we verified the veracity of the sources identified this way using variability as an independent tracer of stellar nature. Of the 35 stars seen to vary with 99% confidence, 34 of them are identified as cluster members by the quartile approach. This gives us great confidence in this method among the bright sources. Ten percent of the cluster members with over 30 counts are seen to flare. This gives a flare rate of one flare per 775 ks.

3. We studied several thermal plasma models and conclude that the Raymond-Smith model is most appropriate for these sources. The cluster members have a typical plasma temperature of 2.9 keV with a mean absorption of $2.8 \times 10^{22} \text{ cm}^{-2}$. By comparing the infrared observed extinction with the fitted $N_H$, we derive a best fit of $N_H = A_V(2.0 \times 10^{21}) \text{ cm}^{-2}$.

4. The center of the cluster is located at 08°59′40″, −47°30′44″ (J2000.0) and has a peak central density of $\sim 400$ X-ray sources per parsec$^{-2}$ in the central 0.1 pc, assuming a 1.7 kpc distance of RCW 38. The density of the number of sources per square parsec is $\sim \exp(-0.5 d)$, where $d$ is the distance in parsecs from the cluster center. The cluster is highly centrally condensed, with a half-width at half-maximum density of 0.2 pc.

5. Since the exposure only reached $L_X \sim 30$, we only detected between 15% and 25% of the members based on comparison with the ONC. Thus, the true peak density is about 1600 stars pc$^{-2}$ in the central 0.1 pc. A similar extrapolation of X-ray-detected members to total membership puts the total membership between 1400 and 2400.

6. We find it highly unlikely that the diffuse emission reported by Wolk et al. (2002) is the result of the 1000–2000 stars not detected as individual X-ray sources. This is because the spectrum of the diffuse emission is distinctly nonstellar, the extent of the diffuse emission is greater than that of the cluster, and there are more photons present in the diffuse emission than would be expected from the nondetected point sources. The point sources may be responsible for the diffuse emission in the central 0.25.

7. The KLF of the X-ray sources appears quantitatively similar to that of the non-X-ray-selected sample, indicating that the X-ray sample is not particularly biased except at the lowest masses. Uncertainties in the various mass tracks make stating a value for the completeness limit, in terms of stellar mass, meaningless.

8. About 150 of the X-ray cluster members are matched to NIR sources in the 2MASS catalog or in our VLT observations of the center of the RCW 38 cluster. Less than one-third of the X-ray-selected sample of cluster members with NIR colors appears to have optically thick disks. In addition, there are 353 non-X-ray-emitting infrared sources in the central 2.5 $\times$ 2.5′ detected by the VLT. The bulk of these (at least 90%) are cluster members. Based on the NIR colors, at least 50% of these non-X-ray-detected infrared sources possess disks. This indicates a bias of the X-ray sources against having disks that are optically thick at the $K$ band.

9. We identify 31 OB star candidates in the field, assuming an age of 0.5 Myr. This number is consistent with the number of OB stars expected for a cluster with about 2000 members. If we had assumed a cluster age of 1 Myr, we would have identified over 60 OB stars. This is inconsistent with the size of the cluster and is taken as evidence for the younger age. A continuum of stellar ages is probably present, as there are still protostellar candidates in the cluster, in particular associated with the IRS 1 ridge.

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