X-RAY EMISSION FROM STRONGLY ASYMMETRIC CIRCUMSTELLAR MATERIAL IN THE REMNANT OF KEPLER’S SUPERNOVA

MARY T. BURKEY, STEPHEN P. REYNOLDS, KAZIMIERZ J. BORKOWSKI, AND JOHN M. BLONDIN

Department of Physics, North Carolina State University, Raleigh NC 27695-8202, USA: reynolds@ncsu.edu

Received 2012 October 24; accepted 2012 December 18; published 2013 January 28

ABSTRACT

Kepler’s supernova remnant resulted from a thermonuclear explosion, but is interacting with circumstellar material (CSM) lost from the progenitor system. We describe a statistical technique for isolating X-ray emission due to CSM from that due to shocked ejecta. Shocked CSM coincides well in position with 24 μm emission seen by Spitzer. We find most CSM to be distributed along the bright north rim, but substantial concentrations are also found projected against the center of the remnant, roughly along a diameter with position angle ~100°. We interpret this as evidence for a disk distribution of CSM before the supernova, with the line of sight to the observer roughly in the disk plane. We present two-dimensional hydrodynamic simulations of this scenario in qualitative agreement with the observed CSM morphology. Our observations require Kepler to have originated in a close binary system with an asymmetric giant branch star companion.

Key words: ISM: individual objects (G4.5+6.8) – ISM: supernova remnants – supernovae: general – X-rays: ISM

1. INTRODUCTION

The remnant of Kepler’s supernova (SN) of 1604 (“Kepler” henceforth) has defied classification since its optical recovery in 1943 (Baade 1943) because of its awkward combination of clear evidence for dense circumstellar material (CSM; originally identified through an optical spectrum indicating enhanced N; Minkowski 1943), suggesting a core-collapse SN, and light identified through an optical spectrum indicating enhanced N; clear evidence for dense circumstellar material (CSM; originally

2. OBSERVATIONS

Kepler was observed for 741 ks with the Chandra X-Ray Observatory ACIS-S CCD camera (S3 chip) between 2006 April and July. Data were processed using CIAO version 3.4 and calibrated using CALDB version 3.1.0. A large background region to the north of the remnant (covering most of the remaining area on the S3 chip) was used for all spectra. Spectral analysis was performed with XSPEC version 12 (Arnaud 1996). We used the nonequilibrium-ionization (NEI) version 2.0 thermal models, based on the APEC/APED spectral codes (Smith et al. 2001) and augmented by the addition of inner-shell processes (Badenes et al. 2006). There are a total of about 3 × 10^7 source counts, with fewer than 3% background (though some of those may be dust-scattered source photons).

3. GAUSSIAN MIXTURE DECOMPOSITION

Our earlier study (Reynolds et al. 2007) showed that spectral variations occur over arcsecond scales, too small for full spectra of individual regions to have adequate statistics. This also means that simple imaging in different spectral bands is incapable of producing quantitative information characterizing regions of different spectral character. In order to concentrate regions with similar spectra for detailed spectral analysis, we instead collect regions of similar spectral character by describing each with four broadband colors and clustering them in a four-dimensional color space using a collection of Gaussian probability distributions (clusters). (Such a probabilistic description of multi-dimensional data is known in the literature as a Gaussian mixture model.) The clusters are now of much higher signal to noise than individual small regions (selected by
eye, for instance, as in Reynolds et al. 2007) and were selected with objective criteria. Gaussian mixture models are well known in many areas of science and are becoming more widely used for a variety of applications in astrophysics (e.g., Shang & Oh 2012; Lee et al. 2012; Hurley et al. 2012).

The integrated spectrum of Kepler is dominated by ejecta emission from Fe, Si, and S, while O and Mg are expected to be primarily found in CSM. We therefore selected spectral bands to feature the oxygen Lyσ line (0.3–0.72 keV), the iron L shell region (0.72–1.3 keV), the magnesium Kα line (1.3 keV–1.5 keV), and the silicon and sulfur Kα lines (combined because of similar characteristics and behavior in the spectrum: 1.7–2.1 keV and 2.3–2.7 keV, respectively). Other elements can contribute in these bands, for instance, Ne Kα and Lyα in the Fe L region, but the integrated spectra show that these contributions are less significant. Each of the previous energy bands was divided by the flux in unused energy bands (1.5–1.7, 2.1–2.3, and 2.7–7.0 keV), so that the entire spectral range was used. This gave the best signal-to-noise ratio for those fluxes, but at the cost of including some line emission in the quasi-continuum bands. However, the quasi-continuum is broad enough to allow maximum contrast with the line features we chose to highlight.

(Insisting on using a more line-free continuum, such as 4–6 keV, has two drawbacks: first, since far fewer counts are present there, the ratios we seek to classify would have much higher statistical noise; and second, one cluster in particular that we identify, that of synchrotron emission, is actually less evident in 4–6 keV emission than in broader bands.) The strong contrast in the clusters we identify, as seen in Figure 2, shows that we are not unduly hampered by the presence of some line emission in our quasi-continuum band.

We divided the observation into about 5000 segments with sizes adjusted to produce comparable numbers of counts (about 6000 each) and extracted the counts in the four line bands plus continuum for each. We then produced a four-dimensional scatter plot of all 5000 segments using the logs of normalized band counts. Using the publicly available software package mclust written in R (Fraley et al. 2012), we decomposed the four-dimensional distribution into several four-dimensional Gaussian clusters, each characterized by at most 15 parameters: its weight relative to other clusters, a center in each of four coordinates, and a (symmetric) 4 × 4 covariance matrix. The number of Gaussians required was found by the algorithm using the Bayesian information criterion (BIC), which was optimized for nine clusters. However, the clusters corresponding to CSM emerged clearly for any total number of clusters between five and ten.

In the Gaussian mixture model, each segment is associated with a set of probabilities of belonging to each of the clusters. We will from now on refer to each cluster more narrowly as a set of segments that have the highest probability of belonging to this cluster. Figure 1 shows the spatial distribution of the segments making up each cluster. The tendency of segments of similar spectral character to form contiguous regions gives us confidence in the method. Summed spectra of all segments in several clusters are shown in Figure 2. We shall refer to the clusters by abbreviations for their colors in Figure 1: R (red), O (orange), Y (yellow), LG (light green), DG (dark green), LB (light blue), DB (dark blue), P (purple), and B (black). The values of the count ratios that define the center of each cluster are given in Table 1.

![Figure 1. Top: merged image between 0.3 and 8 keV (Reynolds et al. 2007). Red: 0.3–0.72 keV; green, 0.72–1.7 keV; blue, 1.7–8 keV. All three images were smoothed using platelet smoothing (Willett 2007). Image size is 4.7 × 3.9. Bottom: division of Kepler into clusters (regions of similar spectral character). Colors are arbitrary. Region R (red) contains the bulk of the CSM, while purple (P) is dominated by synchrotron emission. Most of the rest is ejecta. See the text for further details.](image)

Table 1

| Energy Band | B | P | DB | LB | DG | LG | Y | O | R |
|-------------|---|---|----|----|----|----|---|---|---|
| O           | 0.89 | 0.73 | 1.01 | 1.13 | 1.1 | 1.11 | 1.23 | 0.87 | 1.05 |
| Fe          | 1.2 | 1.07 | 1.35 | 1.49 | 1.44 | 1.47 | 1.68 | 1.31 | 1.39 |
| Mg          | 0.9 | 0.87 | 0.96 | 1.02 | 0.97 | 1.03 | 1.07 | 0.89 | 1.05 |
| Si/S        | 1.1 | 0.97 | 1.11 | 1.19 | 1.16 | 1.17 | 1.19 | 1.13 | 1.14 |

Notes. Entries are the logarithms of ratios of counts in the four energy bands to continuum at the centers of each of the nine clusters identified by the Gaussian mixture method. Bands are described more fully in the text.
Figure 2. Top: spectra of primary CSM regions compared to ejecta-dominated region LG. Top: total of region R. Next: region LG. Third: west-central part of region R, with local background subtracted; dotted curve is the CSM component from the multicomponent spectral fit described in the text. Bottom: small knot in central region with local background subtracted, reproduced from Reynolds et al. (2007). Notice the clear O and Mg features in all three CSM spectra. Bottom: spectra of primary ejecta regions compared to the synchrotron region and region R. Comparable in strength to region R is region LB; note the difference in shape near the peak due to Fe L dominance of region LB. In order of decreasing brightness at 1 keV: regions LG, DG, DB, Y, B, P (synchrotron), and O.

is almost featureless. Regions R, DB, and B contain the clearest Mg feature, suggesting CSM. These regions are compared in the two spectral plots of Figure 2. The vast majority of the CSM is contained within region R. Confirmation of this separation’s effectiveness is evidenced by comparing region R to the Spitzer 24 μm image of SN1604 (Figure 3; Blair et al. 2007) which highlights the heated dust that is evidence of CSM. The two images are extremely similar.

We can examine this issue more closely. Figure 2 shows the integrated spectrum of region R (red, top), along with region LG (green, second from top), west-central portion of region R (third from top) with local background subtracted, and finally the spectrum of a small knot reproduced from Reynolds et al. (2007), also with a local background subtracted (bottom). The west-central spectrum also shows the CSM component from a multicomponent fit (dotted line; see below). The contrast between regions R and LG is evident: the different peak energies result from a higher contribution from Ne in region R and from Fe L in region LG. Region R also shows a feature between 0.6

Figure 3. Top: region R (contours) plus an IR-bright central subregion of region LG superposed on the 24 μm Spitzer image (Blair et al. 2007). Color scale is in MJy sr⁻¹. Middle: soft X-ray image (counts pixel⁻¹ in 0.3–0.72 keV) from Chandra, with contours of subregions of CSM-dominated region R (contours) plus the IR-bright central LG subregion. Numbers: Mg line-strength surface brightnesses (units: 10⁻⁸ photons cm⁻² s⁻¹ arcsec⁻²). Bottom: region R contours superposed on a smoothed image from 6.2 to 6.8 keV (Fe K). The IR-bright LG subregion overlaps with the peak of central Fe K emission. Note the poor correlation between strong Fe emission and CSM, especially in the west-central region.
and 0.7 keV, O Ly\(\alpha\), which is more obvious in the lower two spectra. The obviously greater prominence of both O and Mg in all of region R (especially in the central emission) and the smaller contribution from Fe confirm the association of those regions with CSM.

While we might expect CSM to be found around the outer edge of the supernova remnant (SNR), its presence across the central region is striking. Blair et al. (1991) first pointed out the presence of nonradiative shocks there, indicating partially neutral upstream material. They found that knots in the eastern part of the central emission showed redshifts of order 500 km s\(^{-1}\) while those in the western part were blueshifted by about \(-600\) km s\(^{-1}\), indicating that the former were on the far side and the latter on the near side, projected against the center. Our completely independent analysis locates the same regions, and we adopt the same interpretation.

4. QUANTITATIVE ANALYSIS OF CSM

The integrated spectrum of region R clearly shows distinctive features consistent with its identification as CSM. Ideally, we would use oxygen as a tracer of CSM, as relatively little O is present in most SN Ia models (e.g., Maeda et al. 2010). However, while an inflection at the energy of O Ly\(\alpha\) (0.65 keV) can be seen in some of the spectra of Figure 2, the substantial absorbing column density makes quantitative analysis difficult. The clearest signal of an element not expected to be synthesized in much quantity in an SN Ia (e.g., Maeda et al. 2010) comes from Mg K\(\alpha\) (1.34 keV), with the absence of Mg Ly\(\alpha\) (1.47 keV) as a constraint. The regions we identify as CSM have weak, but well-isolated and easily characterized, emission features for Mg K\(\alpha\), and we use that line to quantify CSM (Figure 3, center).

We subdivided the CSM-dominated region R into 14 sub-regions and extracted spectra from each. We subtracted background from a large region to the north of the remnant. Spectra were fitted with two Gaussians for the two lines and power-law model for the continuum, between 1.2 and 1.6 keV, yielding line strengths. The Ly\(\alpha\) feature was often negligible. For each subregion, we calculated the line-strength surface brightness (ph cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\)). These values are shown in Figure 3 (center).

The west-central portion of region R, with a surface area of 410 arcsec\(^2\) and an Mg K\(\alpha\) flux of \(4.2 \times 10^{-5}\) ph cm\(^{-2}\) s\(^{-1}\), rivals the bright northern rim in Mg K\(\alpha\) surface brightness. In order to learn more about its plasma properties, we modeled its spectrum with a simple plane shock (\textsc{vpshock} model in XSPEC). As in Reynolds et al. (2007), we assumed an absorbing column density \(N_H = 5.2 \times 10^{21}\) cm\(^{-2}\), Wills et al. (2000) solar abundances were adopted for all elements except for N (fixed to 3\(\times\)solar) and Ne and Mg (that we allowed to vary in the fitting process). The ejecta contribution was modeled by a pure Fe, NEI v1.1 \textsc{vpshock} model plus a separate single-ionization-timescale model \textsc{vnei} containing intermediate-mass (Si, S, Ar, and Ca) elements. (We also added a Gaussian line at 0.73 keV in order to account for missing Fe lines in the NEI v1.1 atomic code.) Ejecta contribute to the spectrum mostly in Fe L- and K-shell lines, and in K\alpha lines of Si, S, and Ar (see Figure 2). The temperature and ionization age of the dominant CSM component are 1.2 keV and 1.1 \(\times\) 10\(^{13}\) cm\(^{-3}\) s\(^{-1}\), and the fitted Ne and Mg abundances are near solar (0.7 and 1.2, respectively). This component is plotted as the dotted curve in Figure 2; it accounts for almost all the emission except for obvious Fe L and K emission. Fits with a more elaborate \textsc{vnei} model with unequal ion and electron temperatures reproduce these results. For an assumed shock velocity of \(\sim 1500\) km s\(^{-1}\) (corresponding to the mean temperature of 2.7 keV), typical for Balmer-dominated shocks in Kepler’s SNR (Blair et al. 1991), electrons are heated first to 0.8 keV at the shock front, and then gain energy through Coulomb collision with ions. Average properties of the shocked CSM in the west-central portion of region R appear typical of Kepler as a whole, although its emission measure of 0.32 \(M_\odot\) \(d_e^2\) cm\(^{-3}\) is only a small fraction of the total emission measure of \(\sim 10\) \(M_\odot\) \(d_e^2\) cm\(^{-3}\) (see Blair et al. 2007 for a discussion of the CSM plasma properties as derived from the spatially integrated \textsc{XMM-Newton} RGS spectrum). Blueshifted optical emission found at this location by Blair et al. (1991) indicates that this material was expelled toward us by the SN progenitor. We also performed a spectral analysis of the adjacent central portion of region R farther south and east that contains redshifted optical emission from material expelled away from us by the SN progenitor. We found the same Ne and Mg abundances there but a slightly higher temperature of 1.5 keV, a somewhat shorter ionization age of \(7.1 \times 10^{10}\) cm\(^{-3}\) s, and a significantly smaller emission measure of 0.078 \(M_\odot\) \(d_e^2\) cm\(^{-3}\). These results may be interpreted as a modest density effect, where the blueshifted west-central portion of the CSM is somewhat denser than the redshifted portion farther south and east.

Although the spatial correlation between region R and the IR emission is reasonably good, it is far from perfect. One reason for this might be superposition of ejecta and CSM along the line of sight. We examined X-ray spectra at an IR bright east-central location (see Figure 3) that is part of the ejecta-dominated LG region. While the Fe L-shell emission dominates, a strong Mg K\(\alpha\) line is also present, with a surface brightness as high as found in central portions of region R. An image in the 6.2–6.8 keV energy range shows a prominent Fe K\alpha-emitting filament intersecting the central CSM band at this location (Figure 3). Apparently, both the CSM and Fe-rich ejecta contribute significantly to the X-ray spectrum of this region. They may even arise from physically adjacent regions, as the collision of Fe-rich ejecta with denser than average CSM might be expected to enhance Fe L- and K-shell emission. But the overall spatial correlation between Fe-rich ejecta (as traced by the Fe K\alpha emission) and the CSM is quite poor in the central regions of the remnant, presumably because of the asymmetric distribution of Fe within the SN ejecta.

5. HYDRODYNAMIC SIMULATIONS

The presence of the band of CSM across the center of Kepler (echoed by the presence of nonradiative K\alpha emission) indicates that this material is seen in projection in front and in back of the remnant. Such a morphology could result from a pre-SN CSM distribution that is predominantly disk-like, as expected for mass loss from AGB stars (see Section 6 below for references), with the line of sight roughly in the plane of the disk. To examine this possibility more closely, we performed two-dimensional hydrodynamic simulations of an ejecta-driven blast wave expanding into an azimuthally varying stellar wind, with density varying by a factor of 10 from pole to equator. Half the wind mass is within \(10^5\) of the equator. We ignored the wind speed as it is a few tens of km s\(^{-1}\), negligible compared to the blast-wave speed. We did not attempt to model the north–south density gradient (Blair et al. 2007), presumably the result of system motion to the north or northwest (Bandiera 1987). We modeled the SN ejecta with an exponential profile.
appropriate for Type Ia explosions (Dwarkadas & Chevalier 1998). We used the well-tested code VH-1, a conservative, finite-volume code for evolving the Euler equations describing an ideal, compressible gas. The details of the numerical simulation follow the procedure described in Warren & Blondin (2012).

Figure 4 shows a stage at which the swept-up CSM mass is about equal to the ejected mass ($1.4 M_\odot$). A torus of shocked CSM occupies the equatorial plane. The lower panel of Figure 4 shows a three-dimensional projection of the model, integrating the square of the density (proportional to emission measure) along lines of sight, with the symmetry axis tilted by $10^\circ$ to the plane of the sky. The result is an incomplete bar of shocked CSM across the remnant center as observed, whose radius is about half that of the extent to the north and south, in rough agreement with the central bar of CSM we observe. While the simulation is only suggestive, it indicates that more detailed study of such a model may lead to an improved understanding of Kepler’s dynamics.

6. DISCUSSION

Our observations of CSM toward the center of Kepler are naturally explained by a disk seen edge-on, while the bright northern rim results from northward motion of the system (Bandiera 1987). Such an asymmetric distribution of CSM is expected from a binary system, where an equatorial disk of enhanced mass loss is likely. Inferences of CSM around at least a few Type Ia SNe continue to accumulate (e.g., SN 2008J, Taddia et al. 2012; PTF11kx, Dilday et al. 2012). In particular, Dilday et al. (2012) infer a substantially asymmetric CSM distribution, suggesting a symbiotic binary progenitor system with mass loss concentrated in the orbital plane (but see Soker et al. 2012 for an alternative explanation that invokes a common envelope stage prior to the SN explosion). In an SD model for Kepler, as required by the CSM, we expect the companion to have been an AGB star. Some AGB stars show dense envelopes accessible to study through molecular emission such as CO; on scales of $10''-20''$, the emission is relatively symmetric (Neri et al. 1998). A few systems seem to require asymmetry, though the incomplete sampling of the three-element IRAM interferometer used by Neri et al. (1998) makes detailed imaging impossible. Additional observational evidence for asymmetric winds from evolved stars is presented by Chiu et al. (2006) and Huggins (2007). On theoretical grounds, we expect that the winds from AGB stars in detached binaries can, through gravitational focusing by the companion, produce highly asymmetric CSM, with density contrasts of 10 or more found in numerical simulations by Mastrodemos & Morris (1999) and characterized by Huggins et al. (2009). Politano & Taam (2011) find that several percent of AGB systems should show such strong asymmetries. In a particular case, three-dimensional simulations of RS Oph (Walder et al. 2008) show very large equator-to-pole density variations on the scale of the orbital separation, averaging to factors of two to three on much larger scales. These simulations do not consider the possibility of a wind from the white-dwarf companion (Hachisu et al. 1996), which would tend to evacuate material perpendicular to the plane of the disk and enhance the equator-to-pole density contrast.

The distribution of strong Fe emission in Kepler is worthy of note. Most Type Ia SN models produce highly stratified ejecta, so most Fe should be in the remnant interior. Where the ejecta impact the dense wind in the equatorial plane, then, one might expect enhanced Fe emission—so in a plane roughly coincident with the plane of central CSM. This does not appear to be the case. Fe Kα emission toward Kepler’s interior is asymmetrically distributed, with one patch near the east-central CSM emission, but less near the west-central CSM. We speculate that one
cause of Fe asymmetry might be the “shadow” in Fe cast by the companion star, blocking the ejection of material in that direction. Pan et al. (2012) estimate that an RG companion can shadow up to 18% of the solid angle from the ejecta of a Type Ia SN, while García-Senz et al. (2012) show that morphological effects of a companion’s shadow can survive for hundreds of years. Further study of Fe in particular in Kepler will allow us to examine this possibility in more detail.

7. CONCLUSIONS

We have used Gaussian mixture decompositions of multicolor X-ray spectral data from the long Chandra observation of Kepler’s SNR to identify and characterize regions of shocked CSM as distinct from the ejecta that dominate the integrated spectrum. We find that shocked CSM is co-located with both nonradiative shocks identified by Hα emission, and with 24 μm dust continuum emission seen with Spitzer. We suggest that the central band of CSM is the remnant of a circumstellar disk seen edge-on. Our two-dimensional hydrodynamic simulation shows that a blast wave encountering an equatorial wind from a companion can naturally produce this morphology. The asymmetry we observe requires a binary progenitor system in which the donor is an evolved AGB star.

This work was supported by the National Science Foundation through award AST-0708224 and by NASA through grant NNX11AB14G. We would like to thank Tim Canty for work on an earlier version of this analysis. The scientific results reported in this article are based on observations made by the Chandra X-Ray Observatory.

REFERENCES

Aldering, G., Antilogus, P., Bailey, S., et al. 2006, ApJ, 650, 510
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis and Systems V, ed. G. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Baade, W. 1943, ApJ, 97, 119
Badenes, C., Borkowski, K. J., Hughes, J. P., Hwang, U., & Bravo, E. 2006, ApJ, 645, 1373
Bandiera, R. 1987, ApJ, 319, 885
Blair, W. P., Ghavamian, P., Long, K. S., et al. 2007, ApJ, 662, 998
Blair, W. P., Long, K. S., & Vancura, O. 1991, ApJ, 366, 484
Borkowski, K. J., Blondin, J. M., & Sarazin, C. L. 1992, ApJ, 400, 222
Branch, D., Livio, M., Jungelson, L. R., Boffi, F. R., & Baron, E. 1995, PASP, 107, 1019
Chiotellis, A., Schure, K. M., & Vink, J. 2012, A&A, 537, A139
Chiu, P.-J., Hoang, C.-T., Dinh-V-Trung, L. J., et al. 2006, ApJ, 645, 605
Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, Sci, 337, 942
Dwarkadas, V., & Chevalier, R. A. 1998, ApJ, 497, 807
Fraley, C., Raftery, A. E., Murphy, T. B., & Scrucca, L. 2012, Technical Report 597, Department of Statistics, University of Washington (http://www.stat.washington.edu/mclust/)
García-Senz, D., Badenes, C., & Serichel, N. 2012, ApJ, 745, 75
Hachisu, I., Kato, M., & Nomoto, K. 1996, ApJL, 470, L97
Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 2003, Natur, 424, 651
Hillebrandt, W., & Niemeyer, J. C. 2000, ARA&A, 38, 191
Huggins, P. J. 2007, ApJ, 663, 342
Huggins, P. J., Mauron, N., & Wirth, E. A. 2009, MNRAS, 396, 1805
Hurley, P. D., Oliver, S., Farrah, D., Wang, L., & Efstathiou, A. 2012, MNRAS, 424, 2069
Kinugasa, K., & Tsunemi, H. 1999, PASJ, 51, 239
Lee, K. J., Guillemot, L., Yue, Y. L., Kramer, M., & Champion, D. J. 2012, MNRAS, 424, 2832
Maeda, K., Röpke, F. K., Fink, M., et al. 2010, ApJ, 712, 624
Mastrodemos, N., & Morris, M. 1999, ApJ, 523, 357
Minkowski, R. 1943, ApJ, 97, 128
Neri, R., Kahane, C., Lucas, R., Bujarrabal, V., & Loup, C. 1998, A&AS, 130, 1
Pan, K.-C., Ricker, P. M., & Taam, R. E. 2012, ApJ, 750, 151
Patnaude, D. J., Badenes, C., Park, S., & Laming, J. M. 2012, ApJ, 756, 6
Politian, M., & Taam, R. E. 2011, ApJ, 741, 5
Reynolds, S. P., Borkowski, K. J., Hwang, U., et al. 2007, ApJL, 668, L135
Sankrit, R., Blair, W. P., Delaney, T., et al. 2005, ASPConfProc, 35, 1027
Schaefter, B. E., & Pagnotta, A. 2012, Natur, 481, 164
Shang, C., & Oh, S. P. 2012, MNRAS, 426, 3435
Smith, R. K., Brickhouse, N. S., Liedahl, D. A., & Raymond, J. C. 2001, ApJL, 556, L91
Soker, N., Kashi, A., García-Berro, E., Torres, S., & Camacho, J. 2012, arXiv:1207.5770
Taddia, F., Stritzinger, M. D., Phillips, M. M., et al. 2012, A&A, 545, L7
Velázquez, P. F., Vigh, C. D., Reynoso, E. M., Gómez, D. O., & Schneider, E. M. 2006, ApJ, 649, 779
Walder, R., Folini, D., & Shore, S. N. 2008, A&A, 484, L9
Warren, D., & Blondin, J. M. 2012, MNRAS, in press
Willett, R. 2007, in ASP Conf. Ser. 371, Statistical Challenges in Modern Astronomy IV, ed. G. J. Babu & E. D. Feigelson (San Francisco, CA: ASP), 247
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2012, ApJ, 755, 3
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914