IMPACTS OF THE DETECTION OF CASSIOPEIA A POINT SOURCE

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ABSTRACT
Very recently the Chandra first light observation discovered a point-like source in the Cassiopeia A supernova remnant. This detection was subsequently confirmed by the analyses of the archival data from both ROSAT and Einstein observations. Here we compare the results from these observations with the scenarios involving both black holes (BHs) and neutron stars (NSs). If this point source is a BH, we offer as a promising model a disk-corona type model with a low accretion rate in which a soft photon source at \( \sim 0.1 \) keV is Comptonized by higher energy electrons in the corona. If it is an NS, the dominant radiation observed by Chandra most likely originates from smaller, hotter regions of the stellar surface, but we argue that it is still worthwhile to compare the cooler component from the rest of the surface with cooling theories. We emphasize that the detection of this point source itself should potentially provide enormous impacts on the theories of supernova explosion, progenitor scenario, compact remnant formation, accretion to compact objects, and NS thermal evolution.

Subject headings: stars: neutron — supernovae: general

1. INTRODUCTION

Cassiopeia A is an interesting supernova (SN) remnant in various aspects. The remnant is very young, about 320 yr old. This ring-shaped (e.g., Holt et al. 1994) remnant is associated with jetlike structures (Fesen, Becker, & Blair 1987). The observed abundances of heavy elements are in good agreement with the yields of a massive star (e.g., Hughes et al. 2000). The overabundance of nitrogen found in some knots (Fesen et al. 1987) implies that the progenitor was a massive Wolf-Rayet star (WN type) that has lost most of its H-rich envelope during the pre-SN evolution. The SN was suggested to be faint (Ashworth 1980), which implies that the progenitor was not a red supergiant possibly due to loss of its H-rich envelope.

Recently the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-ray satellite observed Cas A and found a pointlike source (Tananbaum et al. 1999). Subsequently, Aschenbach (1999) reported that the ROSAT/HRI image of Cas A taken during 1995–1996 also shows the pointlike source at a similar location. Very recently, Pavlov et al. (2000) and Chakrabarty et al. (2000) reported the results of their detailed analyses of the Cas A point-source data from the Chandra observation. These authors convincingly argue that the observed point source should, indeed, be a compact remnant of the SN explosion. The single power-law fit to the Chandra data by Pavlov et al. (2000) yields a higher photon index \( \Gamma \) and lower luminosity \( L \) than those observed from typical young pulsars. The spectrum can be equally well fit by thermal models. The best fit for a one-component blackbody model yields the temperature \( T^* = 6–8 \) MK, the effective radius \( R^*_1 = 0.20–0.45 \) km, and the bolometric luminosity \( L^* = (1.4–1.9) \times 10^{37} \) ergs s\(^{-1}\). (In this Letter, the temperature \( T^* \) and luminosity \( L^* \) refer to the values to be observed at infinity.) Chakrabarty et al. (2000) obtained similar results. The size is too small for a 10 km radius neutron star (NS), but it is consistent if the dominant emission comes from localized hot spots. Pavlov et al. (2000) find that the spectrum is equally well fit by a two-temperature thermal model with hydrogen polar caps and the rest of the cooling NS surface composed of Fe. These authors also analyzed the archival data from ROSAT and Einstein and report that the results are consistent with the Chandra results within the 1 \( \sigma \) level. Their data analyses of the point source showed no statistically significant variability (both long and short timescale) over the Einstein-Chandra period. Chakrabarty et al. (2000) carried out detailed timing analysis and report that the 3 \( \sigma \) upper limit on the sinusoidal pulsed fraction is less than 25\% for period \( P > 100 \) ms, less than 35\% for \( P > 5 \) ms, and less than 50\% for \( P > 1 \) ms.

We emphasize here that the detection of the point source itself is extremely important, whether it turns out to be an NS or a black hole (BH). In this Letter, therefore, we will consider both cases. Although the currently available data are not sufficient to distinguish between these options, the most recently completed long Chandra observation by S. Holt et al. (2000)\(^1\) and already planned long XMM observations should be able to do so. Therefore, we consider that it is extremely important and timely now to discuss the implications and offer some predictions for each case.

2. ACCRETING BLACK HOLE

If the Cas A progenitor is more massive than \( \sim 25 M_\odot \), a BH may be formed in the explosion (e.g., Ergma & van den Heuvel 1998). After formation, the inner part of the ejected matter may fall back onto the BH because of the presence of a deep gravitational potential well or a reverse shock. The

\(^1\) Available at http://asc.harvard.edu/targets/summary_observed_daily.html.
property of an accreting BH depends strongly on whether or not an accretion disk is formed. Here we present plausible BH scenarios based on the disk accretion model under the following observational constraints (see, e.g., Pavlov et al. 2000): (1) the single power-law X-ray luminosity of intermediate brightness \( L_x(0.1-5.0 \text{ keV}) = (2-60) \times 10^{34} \text{ ergs s}^{-1} \) for distance \( d = 3.4 \) kpc, which is much lower than the Eddington luminosity, \( L_{\text{Edd}} \approx 7.5 \times 10^{38}(M_{\text{BH}}/3 M_\odot) \text{ ergs s}^{-1} \) for hydrogen-free matter, (2) no significant variability detected between the Einstein and Chandra observations, (3) large \( F/\nu_{\text{opt}} \) (\( \approx 100 \)), and (4) large power-law photon index, \( \Gamma \approx 2.6-4.1 \).

In our model, we assume that the fallback disk has specific angular momentum greater than \( \sim (GM_{\text{BH}}r_s)^{1/2} \) (where \( r_s \) is the Schwarzschild radius) and thus a fallback disk is formed. There is no efficient mechanism for angular momentum removal, since the Cas A compact remnant is unlikely to have a binary companion (§ 4). Then the disk evolution most likely obeys the self-similar solution in which the total angular momentum within the disk is kept constant (Pringle 1974; Mineshige, Nomoto, & Shigeyama 1993). This solution predicts that disk luminosity decays in a power-law fashion after the disk is formed (Mineshige et al. 1997) as

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l \equiv \frac{L}{L_{\text{Edd}}} \sim 10 \left( \frac{M_{\text{fallback}}}{0.1 M_\odot} \right) \left( \frac{\alpha}{0.1} \right)^{-1.3} \left( \frac{t}{320 \text{ yr}} \right)^{-1.3} \left( \frac{M_{\text{BH}}}{3 M_\odot} \right)^{-1.15},
\]

where \( M_{\text{fallback}} \) is the amount of fallback material and \( \alpha \) is the viscosity parameter. We should allow a factor of 0.1–10 changes depending on the distribution of matter and angular momentum. In order for the BH accretion scenario to be consistent with the observed \( l \sim 10^{-4} \) at 320 yr, the amount of the fallback material should indeed be very small, \( M_{\text{fallback}} \sim 10^{-6} M_\odot \). Although the accretion models predict luminosity decrease during the last 20 yr from the Einstein (in 1979) to the Chandra (in 1999) observations, it is small, only about 10\%: \( (320/300)^{1.3} \sim 0.90 \). Since the Einstein observations include larger error bars, more than several tens of percent, the luminosity drop of this level cannot be detected, which is consistent with the lack of observed long-range large-scale variability.

The luminosity of \( \sim 10^{34} \) ergs s\(^{-1} \) is typical to Galactic BH candidates (GBHCs) during quiescence. However, constraint 3, the large \( F/\nu_{\text{opt}} \) ratio, rules out models that invoke formation of a fallback disk whose properties are similar to those in quiescent GBHCs (Chakrabarty et al. 2000). In the case of usual GBHCs, hydrogen-rich matter is continuously added to the disk from the binary companion. According to the disk-instability model for outbursts of GBHCs (Mineshige & Wheeler 1989), a part of the transferred material is accumulated in the outer parts of the disk, which inevitably produces large optical flux in the quiescent GBHCs. Also constraint 4, a large photon index \( \Gamma \), is in conflict with the ADAF (advection-dominated) model for the quiescent GBHCs (Narayan, McCintock, & Yi 1996). For any ADAF models in which soft photons are provided only by internal synchrotron emission and no external soft photons are available, the power-law photon indices should be as small as \( \Gamma \sim 1.7 \) (Tanaka & Lewin 1995). These are the reasons that Chakrabarty et al. (2000) did not favor an accreting BH model for the Cas A source.

Here we propose a different promising BH model, a disk-corona type model, for which the above analogy to the GBHC is not valid. First, we consider constraint 3, the large \( F/\nu_{\text{opt}} \) ratio. In our model for Cas A, there is no binary companion which supplies mass at 320 yr (§ 4). This means that the outer disk boundary is not extended enough to emit significant optical fluxes. The disk is stable due to the smaller disk size and the different composition of the disk material (mostly heavy elements with possibly a little He but no hydrogen; § 4), i.e., the thermally unstable outer zones are absent. In the absence of an instability, the mass-flow rate in the disk is close to constant (Mineshige et al. 1993). Then according to the standard disk model, the effective temperature is \( T_r \sim 4000(M_{\text{BH}}/3 M_\odot)^{1/2}(r/10^6 \text{ cm})^{-3/4}(l/10^{-4})^{1/4} \text{ K} \). For the disk size as small as \( r \approx 10^6 \text{ cm} \) and \( l \sim 10^{-4} \), the constraint \( L_{\text{opt}} < 10^{32} \) ergs s\(^{-1} \) is satisfied.

Next consider constraint 4, the large \( \Gamma \). In order to reproduce large photon indices by Compton scattering, we require that the energy input rate into soft photons exceed that into electrons. It is important to note that GBHCs generally exhibit two states, soft and hard, and a large \( \Gamma \) is a characteristic of the soft-state emission which exhibits soft blackbody spectra with \( kT \sim 1 \) keV. The radiation from thermal photons with \( \sim 1 \) keV times the area of the emission region around a typical black hole of \( 3-10 M_\odot \) produces higher luminosity, \( L_x \sim 10^{-10}-10^{-8} \) ergs s\(^{-1} \), than observed from Cas A. However, we emphasize that unlike GBHC no further mass input is available in our model. Then the accretion rate monotonically decreases, and so does the maximum blackbody temperature, as \( T_{\text{max}} \sim 0.1(M/3M_\odot)^{1/4}(l/(10^{-4}))^{1/2} \) keV. Therefore, we get \( T_{\text{max}} \sim 0.1 \) keV for \( l \sim 10^{-4} \), instead of \( \sim 1 \) keV. A large \( \Gamma \) is then naturally obtained in our model, since there is a copious supply of soft photons at \( \sim 0.1 \) keV into electron clouds in the corona from the underlying cool disk (Mineshige, Kusunose, & Matsumoto 1995). In other words, the important model parameter is \( \nu_{\text{opt}}/\nu_{\text{hard}} \) (ratio of compactness parameter of soft photons to that of hard electrons), where the compactness parameter is proportional to the energy output rate divided by the size of the region. For \( \nu_{\text{opt}} > \nu_{\text{hard}} \), we have a large spectral index (\( \Gamma > 2 \)) because of efficient Compton cooling of hard electrons as shown in Mineshige et al. (1995). The spectral slope is rather insensitive to \( M \) and \( M \). The conclusion is that with the low accretion rate and lower soft photon temperature, our Compton model with a disk-corona configuration naturally yields large \( \Gamma \) with the observed luminosity.

3. COOLING NEUTRON STAR

Here let us assume that the observed Cas A point source is an NS. Pavlov et al. (2000) and Chakrabarty et al. (2000) convincingly argue that the dominant radiation observed by Chandra is most likely coming from polar hot spots or the equatorial ring if it is an NS. Our main purpose in this section is to argue that it is still worthwhile to compare with theoretical models the observed upper limit to the cooling NS component (i.e., the radiation from the whole stellar surface excluding the hotter, localized areas).

Pavlov et al. (2000) offered, as a possible model, a two-component thermal model in which the temperature and radius of the polar caps with hydrogen are 2.8 MK and \( \sim 1 \) km, respectively, while the rest of the surface of the 10 km NS consisting of Fe is at 1.7 MK. In this model, the hotter polar caps are the result of higher conductivity of hydrogen as compared with Fe, the temperature difference between the two components is at 1.7 MK. Therefore, we get \( T_{\text{max}} \sim 0.1 \) keV for \( l \sim 10^{-4} \), instead of \( \sim 1 \) keV. A large \( \Gamma \) is then naturally obtained in our model, since there is a copious supply of soft photons at \( \sim 0.1 \) keV into electron clouds in the corona from the underlying cool disk (Mineshige, Kusunose, & Matsumoto 1995). The spectral slope is rather insensitive to \( M \) and \( M \). The conclusion is that with the low accretion rate and lower soft photon temperature, our Compton model with a disk-corona configuration naturally yields large \( \Gamma \) with the observed luminosity.
filled-center (plerions). Cas A is considered to be a prototype of the former, in which radio pulsars are normally not found. Recently, Pacini (2000) emphasized the evidence for the presence of an active NS in at least some of the shell-type SN remnants, although radio pulsars were not found. Also, there is some evidence for significant magnetospheric activities (which can be responsible for polar cap heating) in some NSs in which no radio pulsar has been found. An example is Geminga (e.g., see Tsuruta 1998). Therefore, the apparent absence of a radio pulsar and/or a plerion should not be used as evidence against polar cap heating. Chakrabarty et al. (2000) offers accretion as a possible cause for polar cap heating when the field strength is significant. If it is weak, their accreting NS model offers the hotter component as originating from the equatorial hot ring. In either case, with an additional heat source for the hotter component, a larger temperature difference between the hotter and cooler components is expected, and hence there is no conflict with the possibility of faster nonstandard cooling.

We adopt the conservative upper limit to the cooler component given by Chandra (Pavlov et al. 2000), $L^c < 3 \times 10^{33}$ ergs s$^{-1}$. The NS thermal evolution is calculated with a general relativistic evolutionary code without making the isothermal approximation (Nomoto & Tsuruta 1987; Umeda et al. 1994a; Umeda, Tsuruta, & Nomoto 1994b). Our results are summarized in Figure 1.

The observed upper limit for Cas A is consistent with the “standard” cooling. However, it is still only an upper limit, and if the actual luminosity of the cooler component turns out to be $\sim 10^{33}$ ergs s$^{-1}$ or less, the result will be extremely interesting. This is because then the observed value will be certainly below the standard cooling curve and hence that will be considered the evidence for nonstandard cooling scenarios such as those involving pion and/or kaon condensates, or the direct URCA process (e.g., Umeda et al. 1994a, 1994b). When the particles in the stellar core are in the superfluid state with substantial superfluid energy gaps, the neutrino emissivity $\dot{E}$ is significantly suppressed (e.g., see Tsuruta 1998). In order to examine this effect of superfluidity, we calculated pion cooling for a representative superfluid model with an intermediate degree of suppression, called the E1–0.6 model (see Umeda et al. 1994a). The result is shown as the thin solid curve in Figure 1.

4. CONSTRAINTS FROM PROGENITOR SCENARIOS

Here we discuss whether the formation of an NS or BH is consistent with the current models of stellar evolution and SNe and whether the evolutionary scenarios constrain the radiation processes from the compact source. The overabundance of nitrogen in Cas A implies that the progenitor was a massive WN star that lost most of its hydrogen envelope before the SN explosion. Here we describe two possible evolutionary paths to form such a pre-SN WN star.

One path is the mass loss of a very massive single star. A star with the zero-age main-sequence mass $M_{\text{MS}}$ larger than $\sim 40 M_\odot$ can lose its hydrogen-rich envelope via mass loss due to strong winds and become a Wolf-Rayet star (e.g., Schaller et al. 1992). Recent theoretical models and population synthesis studies suggest that stars with $M_{\text{MS}} \geq 25 M_\odot$ are more likely to form BHs than NSs (e.g., Ergma & van den Heuvel 1998). This implies that the WN star progenitor is massive enough to form a BH. The explosion can be energetic enough to prevent too much matter fallback to be consistent with the small fallback mass inferred in § 2.

The other evolutionary path to form a pre-SN WN star is mass loss due to binary interaction. If the progenitor is in a close binary system with a less massive companion star, the star loses most of its H-rich envelope through Roche lobe overflow. In this case, the WN progenitor can form from a star of $M_{\text{MS}} \approx 40 M_\odot$. Its SN explosion of Type Ib/c would leave either a BH (if $M_{\text{MS}} \sim 25$–$40 M_\odot$) or an NS (if $M_{\text{MS}} \approx 25 M_\odot$). If the compact remnant in Cas A turns out to be an NS, therefore, the progenitor must have been in a close binary system.

In the binary scenario, the companion to the Cas A progenitor cannot be more massive than a red dwarf, as constrained from the $R$- and $I$-band magnitude limit (van den Bergh & Pritchet 1986). When the companion star is such a low-mass star, i.e., the mass ratio between the stars is large, the mass transfer is inevitably nonconservative (e.g., Nomoto, Iwamoto, & Suzuki 1995), and the companion star will spiral-in into the envelope of the Cas A progenitor. In order for most of the H-rich envelope to be removed, the envelope should have been a red giant size so that the orbital energy released during the spiral-in exceeds the binding energy of the envelope. After losing its envelope due to frictional heating, the star became a WN star.

If we take the model of $M_{\text{MS}} = 25 M_\odot$ as an example, the star at the WN stage has $8 M_\odot$. Since the explosion ejects Si and Fe from the deep layers (Hughes et al. 2000), the mass of the compact remnants could not exceed 2–3 $M_\odot$. Then the binary system is very likely to be disrupted at the explosion. In this case, the compact star in the Cas A remnant does not have a companion star, so no mass transfer can be postulated.
The implication is also that the accretion onto the compact remnant can occur only as a result of fallback of the ejected matter, and so the composition of the fallback matter is mostly heavy elements with possibly a small fraction of helium but no hydrogen.

In either the single or binary scenario, the WN star blows a fast wind which collides with the red giant wind material to form a dense shell (Chevalier & Liang 1989). If the red giant wind formed a ringlike shell (due possibly to the spiral-in of the companion), the collision between the supernova ejecta and the shell could explain the observed ringlike structure of Cas A.

5. DISCUSSION AND CONCLUSION

We agree with Chakrabarty et al. (2000) that for Cas A point source the usual ADAF model for a quiescent GBHC hardly reconciles with the observations. However, we emphasized in § 2 that there does exist a very promising BH disk accretion model. In this model, the fallback material is like the soft state of a GBHC with a disk-corona configuration, not like a quiescent GBHC with ADAF. With the low accretion rate and Comptonization of cooler soft photons (∼0.1 keV or less), we naturally obtain a large photon index of γ ∼ 2.6–4.1 and lower luminosity of L ∼ 10^{38}–10^{39} ergs s⁻¹, as observed from the Cas A point source.

Accreting NS models are also possible (see Chakrabarty et al. 2000). However, we can still, without difficulty, distinguish between the BH and NS accretion models because the characteristic properties of the observed X-ray spectra in these two cases are quite different (e.g., see Tanaka 2000). For instance, the radiation from an accreting NS is dominated by thermal emission from the stellar surface (Rutledge et al. 2000), which is absent if a BH is involved.

If the point source is an NS, the dominant radiation observed by Chandra most likely corresponds to the radiation from a localized small area. The detailed studies of theoretical light curves expected from anisotropic cooling of an NS have been carried out by, e.g., Shibanov et al. (1995) and Tsuruta (1998), with the latter including hot spots. The results show that pulsation depends on the relative angles between the rotation axis, the magnetic axis, and the line of sight. Depending on the combinations of these angles, pulsations from zero to up to about 30% are predicted, and so the observed constraints on the pulsed fraction are still consistent with an NS model.

Although the current data of Cas A point-source can be consistent with both BH and NS scenarios, future observations by the Chandra, XMM, and other satellite missions should be able to distinguish between these cases. If distinct periodicity is found, the point source definitely should be an NS. The existence of the NS itself will significantly constrain the progenitor scenario for Cas A. Better spectral information should be able to distinguish between the BH and NS as the compact remnant. If the source is found to be a BH, the implication is significant in the sense that this will offer the first observational evidence for BH formation through an SN explosion and greatly constrain the BH progenitor mass by combining with the abundance analysis of Cas A (Hughes et al. 2000).

In conclusion, we emphasize that the Cas A point source can potentially provide great impacts on the theories of supernova explosion, progenitor scenario, compact remnant formation, accretion to compact objects, and NS thermal evolution.

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