Discovery of Recombining Plasma in G166.0+4.3: A Mixed-Morphology Supernova Remnant with an Unusual Structure

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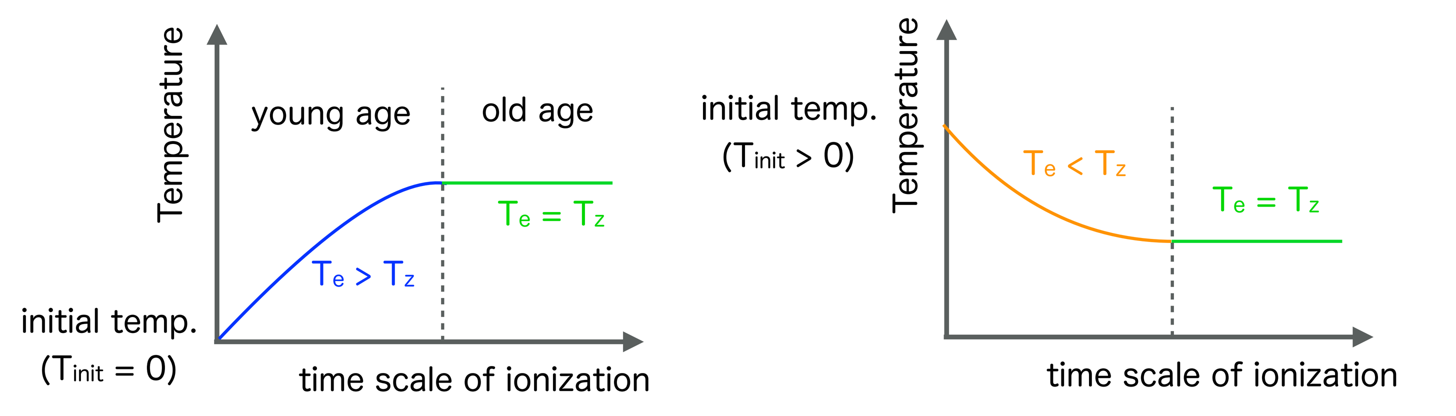
Recombining Plasma in SNRs

☆ Recombining plasmas (RPs) are characterized by a higher ionization temperature (T_z) than an electron temperature (T_e).

☆ The Suzaku satellite has recently discovered RPs in several mixed-morphology supernova remnants which have center-filled thermal X-ray emissions in a synchrotron radio shell [1][2].



blue: Ionizing Plasma (IP) orange: Recombining Plasma (RP)
green: Collisional Ionization Equilibrium (CIE)

☆ Two scenarios of formation process of the RPs:

・Rarefaction scenario [3]:
If the supernova explodes in a dense circumstellar matter (CSM) around the massive progenitor, the ejecta and CSM are shock-heated quickly to CIE or IP, because the ionization timescale is short even in a dense medium. Soon after the shock wave breaks the CSM region out to lower density interstellar medium (ISM). Then the electron temperature cools down by the adiabatic expansion.

・Thermal conduction scenario [4]:
If the normal CIE or IP plasma encounters to cold molecular cloud, the electron energy will be transferred to the molecular cloud by thermal conduction, and hence the electron temperature drops rapidly. Since the recombination timescale of ionized atoms is longer than the conduction time scale, the ionization temperature cannot follow the decrease of the electron temperature, and hence RP would be realized.

A Mixed-Morphology SNR: G166.0+4.3

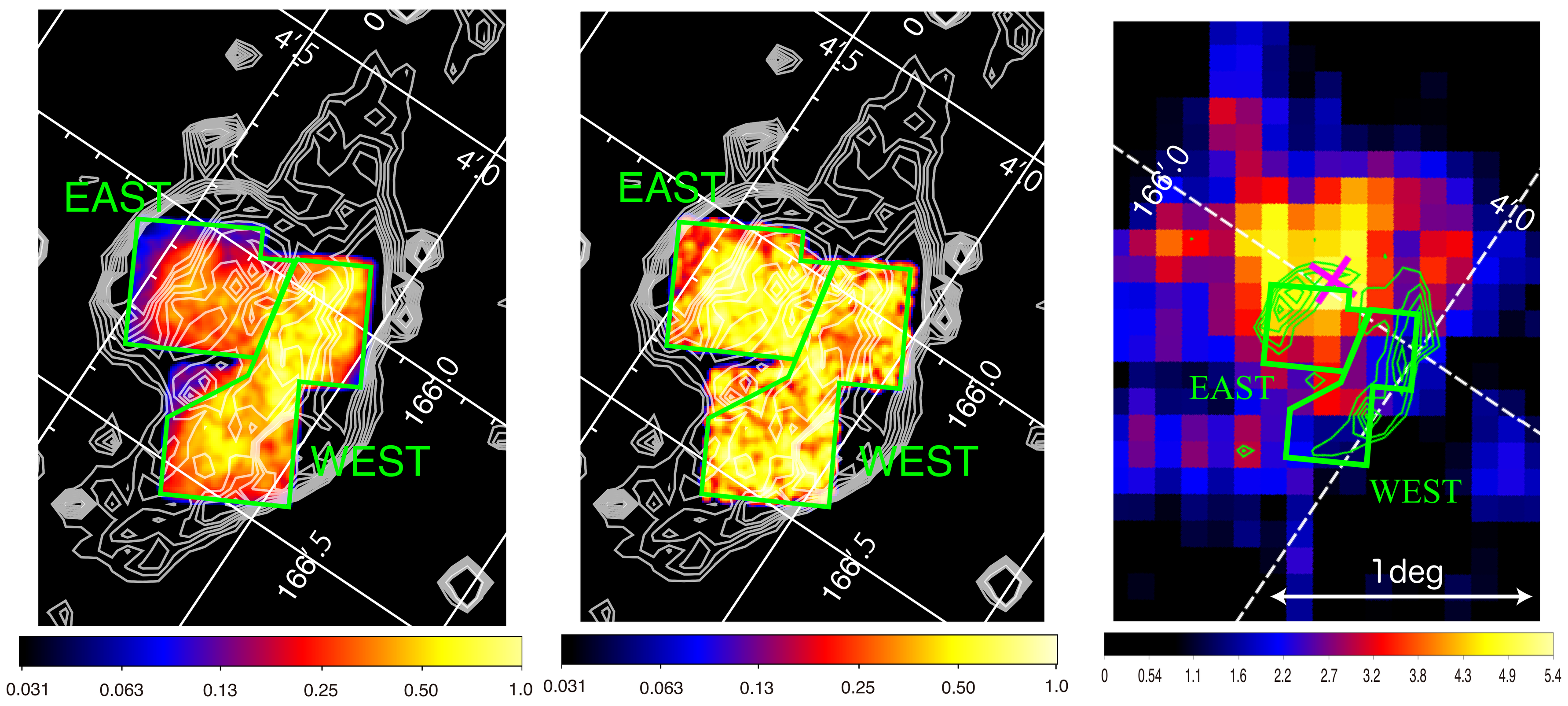
☆ G166.0+4.3 is a mixed-morphology supernova remnant.

☆ The synchrotron radio shell is extremely asymmetric. A large bipolar structure in southwest (WEST region) with a smaller semicircle shell in northeast (EAST region) [5][6].

☆ Araya (2013) [7] discovered a GeV gamma-ray emission from the EAST, suggesting an existing of nearby molecular clouds (right figure).

☆ We have performed a long-time (totally 230 ks) observation of G166.0+4.3 with the Suzaku satellite in 2014.

☆ The left and center figure are the Suzaku X-ray images in the energy band of Fe-L and Si-K. The emission of the Si extends over the whole region of the SNR, while that of Fe is concentrated at the WEST.



・Suzaku X-ray Images (XIS0+1+3) with 325 MHz radio contour.
Fe-L band (0.68-1.60 keV) Si-K band (1.75-2.10 keV)

・Fermi 0.5-2 GeV gamma-ray Image [7]

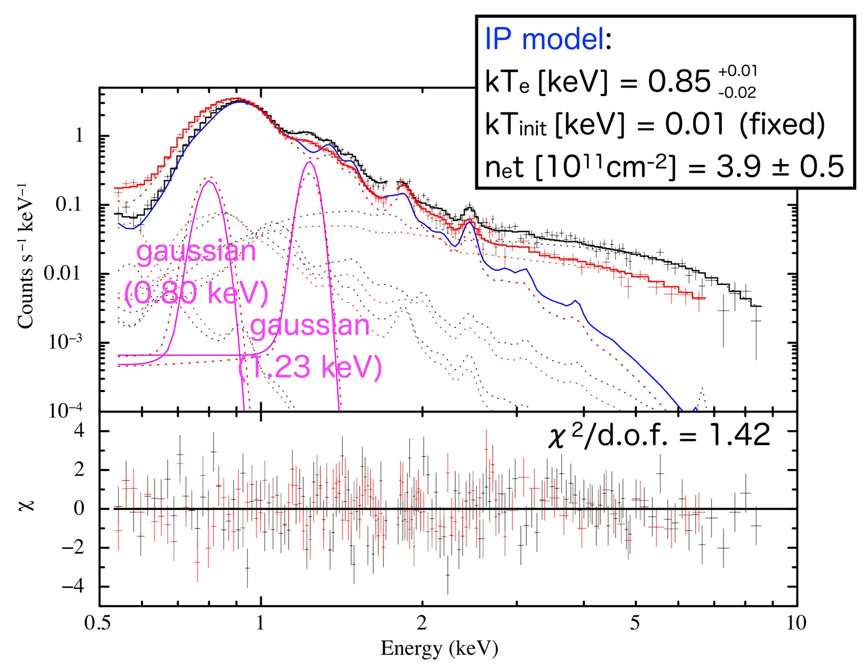
Spectral Analysis

☆ WEST region

・We fit the NXB-sbtracted spectra (black: obtained by FI-CCD, red: obtained by BI-CCD) using the **VVRNEI** model (solid lines) with background model (dotted lines).

・Two gaussian lines (peak-energies: 0.80 keV and 1.23 keV) are added due to the errors for Fe-L lines.

・The plasma of the WEST is well represented by 1-component IP model with the kT_e of 0.85 keV.



k: Boltzmann constant , n_e: electron density, t: time scale of ionization

① Applying a similar IP model of the WEST to the plasma of the EAST, we found large residuals around 2.0 keV and 2.6 keV (corresponding to Si XIII Lyα (2.0 keV) and radiative recombining continuum of Si XIII (2.67 keV) + S XIV Lyα (2.63 keV)).

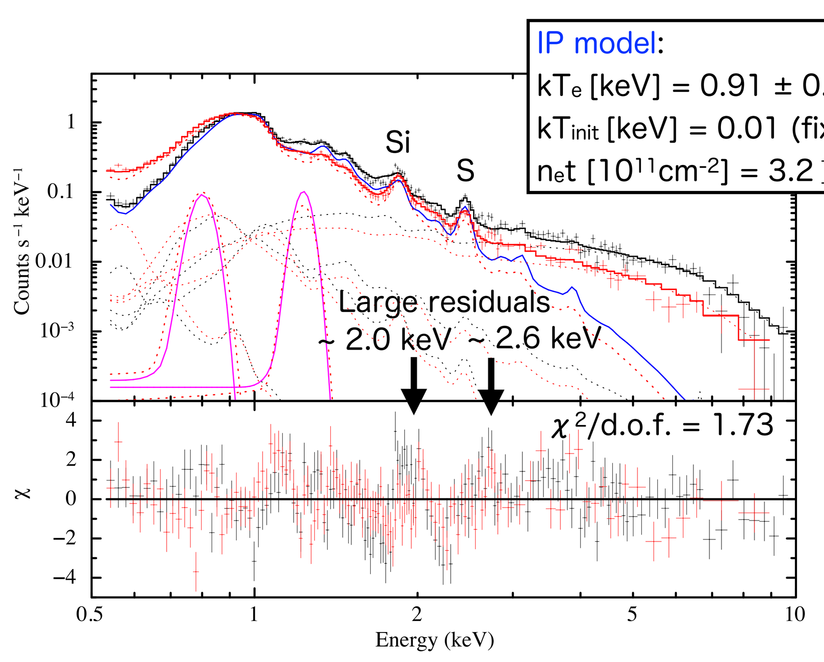
② For detail investigation, we focus on the Si and S lines. We apply a 1-component IP and RP model to the spectra in the energy band of 1.6-10 keV. The plasma demands the RP model with the kT_e of 0.38 keV and the kT_{init} of 3 keV or mode.

③ We apply the RP model to the full band spectra (0.5-10 keV). This fit leaves residuals around Fe-L and Ni-L bands. In the EAST, the locations of Si and Fe are different (see the Suzaku image). The state of the plasma of Fe&Ni and that of other elements may be different, so we split the plasma into two component.

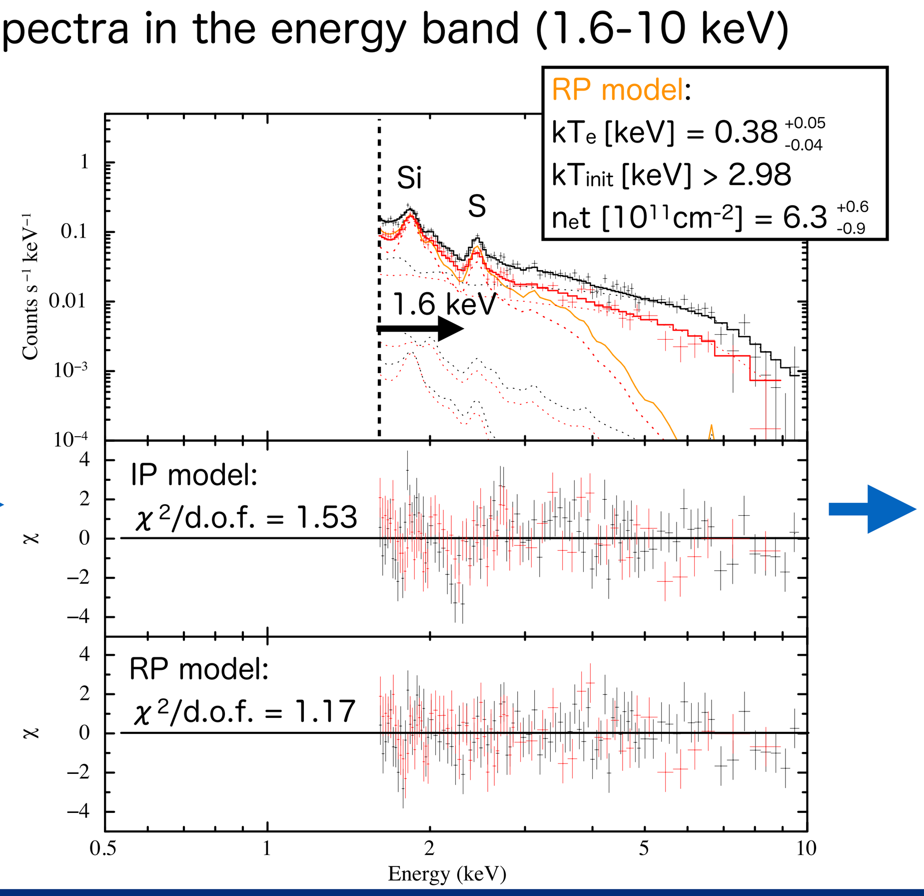
④ We apply a two component (plasma of only Fe&Ni and that of other elements) model. In the result of the fitting, we explain the spectra as a IP (only Fe&Ni) and RP (other elements) model with the kT_e of 0.85 keV and 0.44 keV, respectively.

☆ EAST region

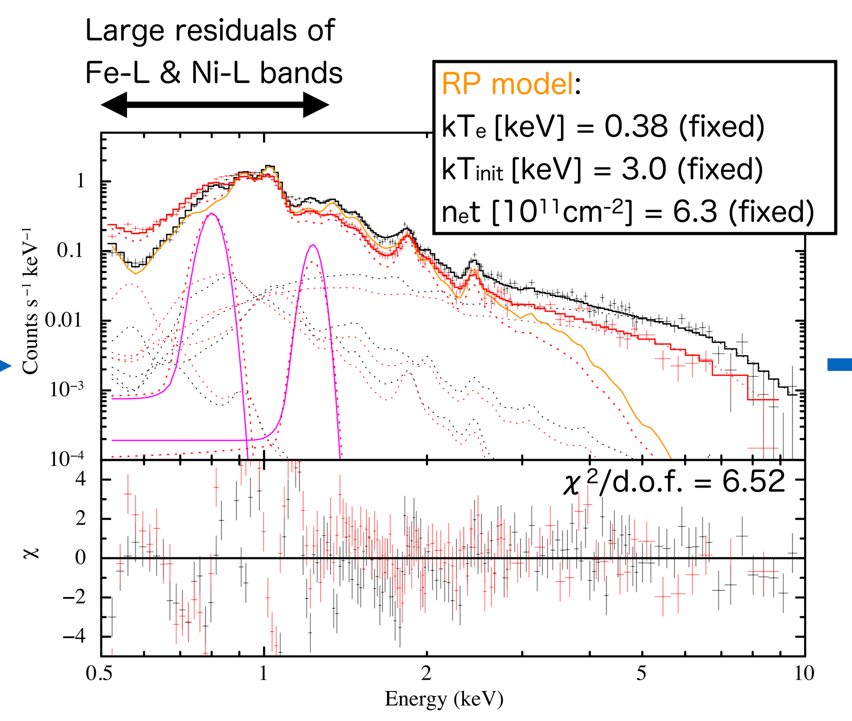
① Applying a 1-component IP model



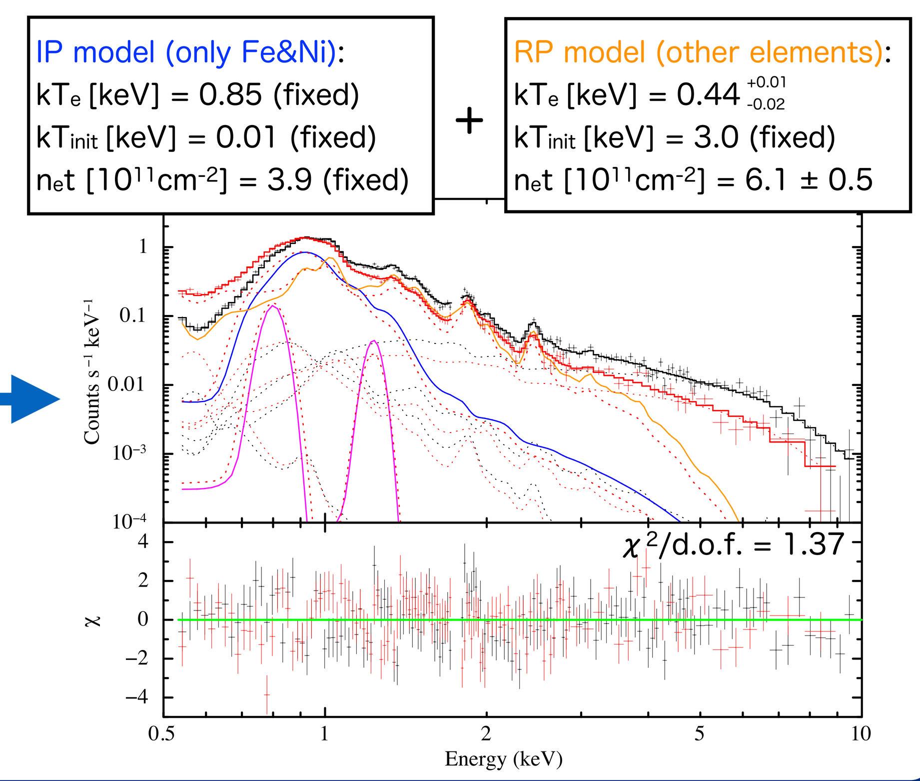
② Applying a 1-component IP/RP model to the spectra in the energy band (1.6-10 keV)



③ Applying a 1-component RP model to full band (0.5-10 keV).



④ Applying a two-component model to full band (0.5-10 keV).



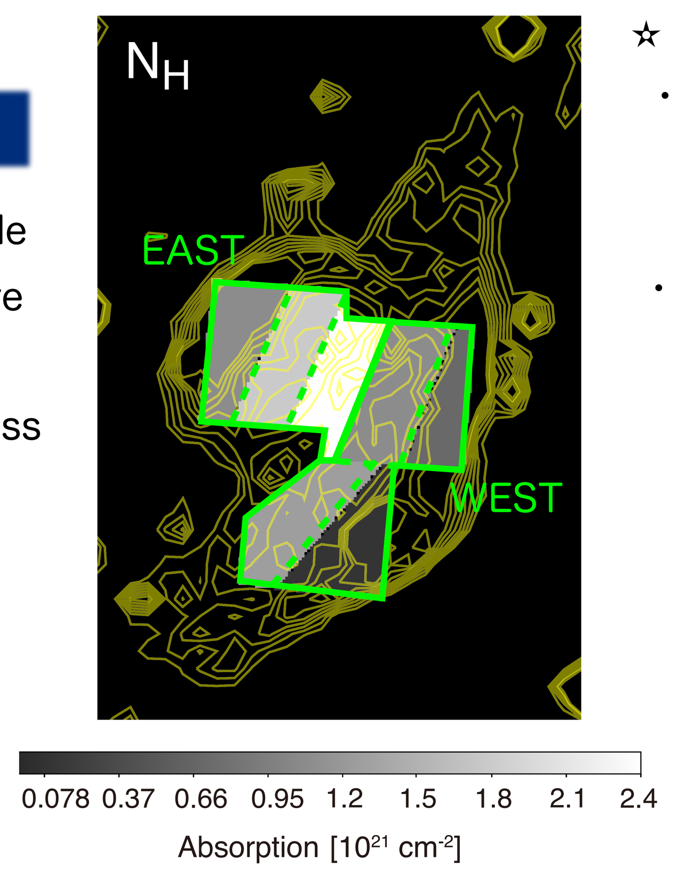
Origin of Recombining Plasma in G166.0+4.3

☆ We discover the RP (elements except Fe&Ni) in the EAST, while the plasma in the WEST and the plasma of Fe&Ni in the EAST are the IPs.

☆ Surrounding environments of SNRs affect the formation process of the RPs. We investigate density environment of the SNR. The figure is column density (N_H) map divided into small regions. Absorption in the side of the EAST is larger than that in the side of the WEST.

→ The environment in the EAST may be dense.

☆ Morphology of the radio shell also suggests environment of low density in the WEST [6].



☆ Considering the two scenarios of formation process of the RPs:

・Rarefaction scenario:
Rarefaction process demands a density distribution changing from a large density to a small density. It is inconsistent with our results.

・Thermal conduction scenario:
The density environment in the EAST suggests existing of nearby molecular clouds, supporting the result of Fermi gamma-ray image [7].

In the outer region of the EAST, a time scale of the thermal conduction is consistent with the SNR age of 2.4 x 10^4 yr [8].

$$t_{cond} \sim 4.2 \times 10^4 (n_e/0.84\ cm^{-3})(l_t/2\times10^{19}\ cm)^2(kT_e/0.44\ keV)^{-2.5}(\ln\Lambda/31.4)\ yr\ [4]$$

l_t: time scale of thermal conduction, Λ: plasma parameter

We explain that the plasma in the WEST and that of Fe&Ni in the inner region of the EAST are the IPs, while that of other elements in the outer region of the EAST became the RP due to the thermal conduction by molecular clouds circumscribed the SNR.

Reference

[1] M. Ozawa et al. 2009, ApJ, 706, L71.
[2] H. Yamaguchi et al. 2009, ApJ, 705, L6.
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[4] M. T. Kawasaki et al. 2002, ApJ, 572, 897.
[5] T. L. Landecker et al. 1982, ApJS, 51, 115.
[6] S. Pineault et al., 1987 ApJ, 315, 580.
[7] M. Araya 2013 MNRAS, 434, 2202.
[8] F. Boochino et al. 2009, A&A, 498,139.