

Scattering of emission lines in galaxy cluster cores: measuring electron temperature

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ABSTRACT

The central galaxies of some clusters can be strong emitters in the Ly α and H α lines. This emission may arise either from the cool/warm gas located in the cool core of the cluster or from the bright AGN within the central galaxy. The luminosities of such lines can be as high as $10^{42} - 10^{44}$ erg/s. This emission originating from the core of the cluster will get Thomson scattered by hot electrons of the intra-cluster medium (ICM) with an optical depth ~ 0.01 giving rise to very broad ($\Delta\lambda/\lambda \sim 15\%$) features in the scattered spectrum. We discuss the possibility of measuring the electron density and temperature using information on the flux and width of the highly broadened line features.

Key words:

1 INTRODUCTION

Centres of most relaxed galaxy clusters host giant visibly prominent elliptical galaxies referred to as the brightest cluster galaxy (BCG). A few of these BCGs show significant star-formation rates, $\sim 10 - 100 M_{\odot}/\text{yr}$, (but also as large as $\sim 740 M_{\odot}/\text{yr}$, see McDonald et al. 2012). As tracers of cool/warm gas, bright emission lines have been observed at the centres of clusters across a wide range of wavelengths. For example Ly α (Hu 1992; Johnstone & Fabian 1995; Baum et al. 2005) and [OII] (McNamara & O’Connell 1989) in UV, H α + [NII] in optical (Heckman 1981; Cowie et al. 1983; Crawford et al. 1999); rotational lines from molecular H₂ (Elston & Maloney 1994; Jaffe & Bremer 1997; Donahue et al. 2000) and CO (Edge 2001; Salomé & Combes 2003); [NeII] and polycyclic aromatic hydrocarbons (PAH) complexes (Donahue et al. 2011). Recent Herschel observations (Mittal et al. 2011, 2012; Corbelli et al. 2012) have also detected atomic cooling lines of [CII], [OI], [NII], providing us with important clues about the thermal state of gas in cluster cores.

It is also well known that the centres of BCG host an Active Galactic Nucleus (AGN) which is powered by the accretion of mass onto the central super-massive ($10^6 - 10^9 M_{\odot}$) black hole. These AGN’s can be extremely luminous across a broad range of frequencies from the Radio to γ -rays. These bright emission lines in the AGN spectra arise as a result of photoionisation of the cold/warm gas by the continuum radiation coming from the centre. Some of the many prominent lines are Ly α , CIV, CIII], MgII, NeV, [OI], [OII], [OIII], [NeII], H α , H β , H γ , [NII], etc., see Netzer (1990); Osterbrock (1988); Véron-Cetty & Véron (2000) for reviews.

The aim of this paper is to highlight the diagnostic potential of the bright emission lines originating from the centres of clusters to measure the ICM properties. These lines should get highly broadened after being Thomson scattered by the hot electrons ($T_e \sim$ few keV) of the ICM (with optical depth, $\tau \sim 0.01$). The width of these broadened lines would be a probe of the line-of-sight (LOS) weighted gas temperature, while the ratio of the flux-density in the scattered and direct continua, would give in optical depth or the LOS-weighted gas density. Thus the ability to measure this scattered signal will open up an alternate and interesting probe of the ICM.

The observations of scattered light from clusters has

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been discussed previously in the literature in various contexts. The possibility of observing beamed AGN radiation scattered by the surrounding gas was discussed by Sunyaev (1982); Gilfanov et al. (1987). The observed alignment between radio and optical emission (in the 3C/3CR radio galaxies), first reported by Chambers et al. (1987), was attributed to the scattering of the beamed emission of the AGN (Fabian 1989) by hot electrons from the intracluster/group gas. The evidence for scattering was further supported by polarimetric observations (di Serego Alighieri et al. 1989). However, subsequent works (see e.g., Dey et al. 1996; Zakamska et al. 2005) ruled out scattering by hot ($T_e \gtrsim 10^4$ K) electrons, as constrained by the observed line widths, instead preferring the scattering by relatively cool gas and dust. Sazonov et al. (2002) considered resonant scattering of X-ray emission from a central AGN by the ambient intracluster gas, proposing it as a method to indicate the parameters of the surrounding hot gas.

Also, Holder & Loeb (2004) proposed that joint observations of scattered radio emission along with the SZ effect could be used to probe the temperature profiles of clusters. The SZ effect probes the quantity $y = \int n_e T_e dl$ while the scattered flux from point sources in radio would probe optical depth $\tau = \sigma_T \int n_e dl$; assuming a β -model for the gas density, they show that temperature measurements could be possible up to a precision of 1 keV. The scattering and polarisation of light at optical wavelengths was discussed by Murphy & Chernoff (1993), however they did not consider the possibility of using the spectral information to measure temperatures.

The outline of this paper is as follows. In section 2 we illustrate the scattering of a single bright line and show the dependence of the broadened profile on the electron temperature. In section 3 we consider the scattering of H α lines in Perseus cluster and compute the surface brightness of the scattered signal as a function of the radius. In section 4 we repeat a similar computation, but now for Ly α and H α lines emitted by the AGN in the bright radio galaxy 3C 295 found within a galaxy cluster. In section 5 we discuss the feasibility of measuring this faint and diffuse scattered signal and outline the requirements for such observations. We also comment on the possibility of exploiting the polarisation information of the scattered signal in the outer envelopes of cD galaxies / intracluster light to improve the chances of detecting the scattered signal. In section 6 we mention the optimal properties of clusters needed for the robust measurement of temperature and optical depths in clusters. We conclude in section 7.

2 BROADENED SPECTRAL PROFILE OF A NARROW BRIGHT LINE

The Thomson scattering of photons by non-relativistic ($k_B T_e / m_e c^2 \ll 1$), electrons having a Maxwellian distribution at temperature T_e is described by a photon redistribution kernel, given by (see Babuel-Peyrissac & Rouvillois

1970; Sunyaev 1980),

$$K(\nu, \boldsymbol{\Omega} \rightarrow \nu', \boldsymbol{\Omega}') = \frac{3}{16\pi} \sqrt{\frac{m_e c^2}{2\pi k_B T_e}} \left(\frac{\nu'}{\nu}\right) \frac{1 + \mu^2}{g} \exp\left\{-\frac{m_e c^2 (\nu - \nu')^2}{2k_B T_e g^2}\right\}, \quad (1)$$

where $\mu = \boldsymbol{\Omega} \cdot \boldsymbol{\Omega}'$ is the cosine of the angle of scattering and $g = \sqrt{\nu^2 + \nu'^2 - 2\nu\nu'\mu}$. Note that this kernel is applicable for single scattering approximation. Throughout this paper we shall consider multi-scattering to be negligible, which is a valid assumption for an optically thin gas (in clusters, $\tau = \sigma_T \int_0^\infty n_e(r) dr \ll 1$). At IR, optical, UV and soft X-ray frequencies and for temperatures $k_B T_e \leq 10$ keV equation 1 is sufficiently accurate, and we shall use this form in the rest of the paper. Sazonov & Sunyaev (2000) provide a more general expression (see their Eq. 7) for the kernel K , applicable in the mildly relativistic regime, up to $k_B T_e \lesssim 25$ keV and $h\nu \lesssim 50$ keV. Note that Sunyaev (1980) (see Eq. 5) and Sazonov & Sunyaev (2000) (see Eq. 19) also give an analytic expression for the above formula in the case of angle-averaged scattering.

Fig. 1 (a) shows the broadened and angle-averaged spectral profile of a single line at 6560 Å using the kernel in equation 1 and assuming a temperature of $T_e = 4$ keV. The three curves correspond to the following intrinsic line shapes: a delta function and two Gaussians with standard deviation of 100 and 500 Å respectively; all having the same central wavelength and same flux in the unscattered line. If the line is intrinsically narrow the angle-averaged scattered line shows a sharp cusp at the wavelength of the line with broad asymmetric wings on either sides (Sunyaev 1980). In the Thomson limit, when a photon is scattered by an electron with velocity \mathbf{v} the energy of the former changes as

$$\frac{\nu'}{\nu} = \frac{1 - \frac{\boldsymbol{\Omega} \cdot \mathbf{v}}{c}}{1 - \frac{\boldsymbol{\Omega}' \cdot \mathbf{v}}{c}}. \quad (2)$$

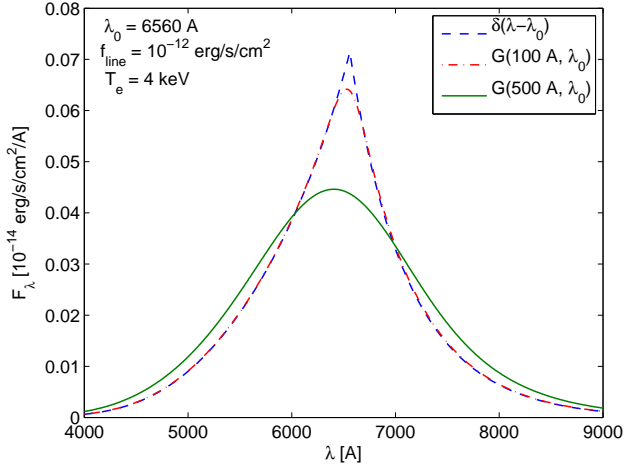
Naively, this suggests that averaging over an isotropic (e.g. Maxwellian) distribution of electrons will lead to a symmetric scattered line profile. However, the rate of scatterings is proportional to $(1 - \frac{\boldsymbol{\Omega} \cdot \mathbf{v}}{c})$, i.e. photons are preferentially scattered by approaching rather than receding electrons. This effect (also generic to the Fermi type-II acceleration mechanism) causes a net change of the photon energy $\propto (\frac{v}{c})^2 \propto kT_e / m_e c^2$ and skews the scattered line profile to the right.

A line with a finite width will cause a smoothing of the cusp. For most bright lines of interest the intrinsic line width is small compared to the broadening caused by the scattering, i.e.,

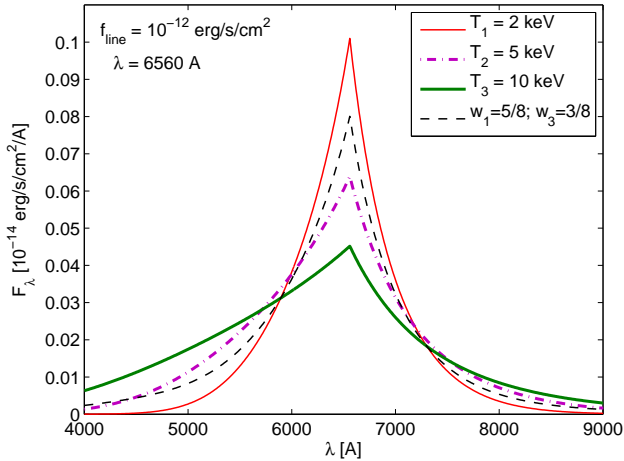
$$\frac{\Delta\lambda}{\lambda} \ll \sqrt{\frac{2k_B T_e}{m_e c^2}} \sim \frac{4 \times 10^4 \text{ km/s}}{c}. \quad (3)$$

For example McDonald et al. (2012) find the width of emission lines between 600 km/s (in the nuclei) to 100 km/s (in the outer filaments). Thus the wings of the broadened line profile are expected to remain unaffected and any change in the shape of the line would occur only near the tip depending on the line width $\Delta\lambda$.

In Fig. 1 (b) we show the effect of gas temperature on the broadening. A useful estimate of the width of the broadened line (see equation 1), is $\Delta\lambda/\lambda \approx 0.2\sqrt{k_B T_e / 10 \text{ keV}}$.



(a) Impact of the intrinsic line width on the angle-averaged scattered profile. Any intrinsic line width causes smearing of the cuspy shape at the tip of the scattered line profile. Here $\delta(\lambda - \lambda_0)$ and $G(\Delta\lambda, \lambda_0)$ denote the intrinsic shape of the emission line – the delta function and the Gaussian profile (with s.d. = $\Delta\lambda$) respectively. Changes in the flux at the wings are seen only when the intrinsic width of the line is comparable/larger than thermal broadening.



(b) Angle-averaged broadened line profile after scattering at various temperatures. Note that the multi-temperature-weighted broadening (thin dashed black), with the weights w_1 and w_3 for the temperatures T_1 and T_3 , is not the same as that produced due to a single but similarly weighted temperature (thick dash-dotted magenta), $T_2 = w_1 T_1 + w_3 T_3$.

Figure 1. Broadened line profile due to scattering (after angle-averaging): effects of intrinsic line width and gas temperatures on the shape of the scattered line. A flux of 1×10^{-12} erg/cm²/s is assumed for the flux in the unscattered line.

At a given projected distance from the cluster centre, the LOS passes through gas at various temperatures. The scattered line will then be broadened by different amounts, weighted by the product of gas and photon density distribution along the LOS. Fig. 1 (b) shows the (angle-averaged) multi-temperature broadening with the LOS weights of 5/8 and 3/8 for temperatures of 2 and 10 keV. One can also see that this weighted profile is different from a single tempera-

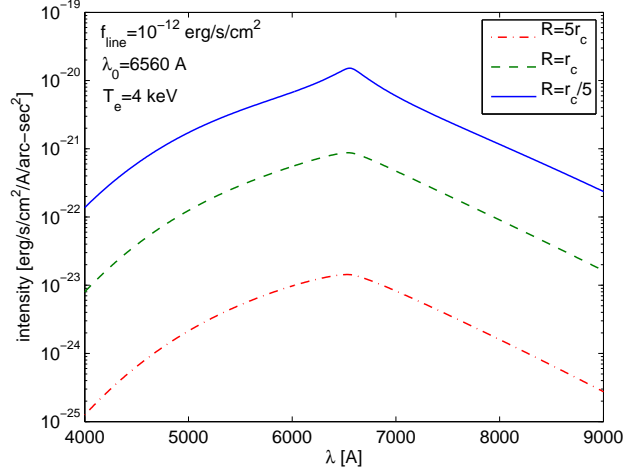


Figure 2. Shape of a single scattered line at various projected distances assuming an isothermal β -model profile for the Perseus cluster. The tip of the profile becomes more cuspy towards the centre due to significant scattering at small angles, while it is flat at larger distances where the scattering occurring at angles close to $\pi/2$ becomes dominant.

ture profile with temperature of 5 keV which is the weighted mean of the two temperatures.

The brightness/intensity of the scattered light from a central isotropic source in a (spherically symmetric) cluster may be derived as follows. Let $P(\nu)$ be the luminosity [erg/s/Hz] of the central source producing the flux $f(\nu, r) = P(\nu)/4\pi r^2$ at the scattering point in the cluster. The surface brightness profile of scattered radiation at the projected distance R is then,

$$I(\nu, R) = \int_l \int_{\nu'} f(\nu, r) K(\nu' \rightarrow \nu, \mu) n_e(r) \sigma_T d\nu' dl \quad (4)$$

where $r = \sqrt{l^2 + R^2}$, $\mu = l/r$, and l is the distance along the LOS.

Fig. 1 shows a thermally broadened line profile due to the angle-averaged scattering of light (emitted by a central point source) from the surrounding gas. One gets a cuspy profile at the tip ($\nu = \nu'$), only when the scattering occurs from regions very close to the central source. In reality deviations (from the highly cuspy profile) are expected owing to the fact that one would typically be interested in observing the scattered light (say in a circular annulus), excluding the highly bright central region emitting directly. Equation 1 shows the dependence of the scattering kernel on the angle of scattering, $\mu = \cos(\theta)$; note that the function $g(\nu, \nu'; \mu) \rightarrow 0$ as $\nu \rightarrow \nu'$ and $\mu \rightarrow 1$ (forward-scattering), causing a sharp cusp at the tip. Thus when the scattered light is observed close to the centre in projection (when small-angle forward scattering is dominant) the broadened line is cuspy; while for the scattered light observed away from the centre (scattering at angles close to $\theta = \pi/2$ dominate) the profile is smooth at the tip. The dependence of the shape of the broadened line for scattered light observed at various values of projected distances is indicated in Fig. 2. We emphasise that this effect should be considered in deducing the gas temperatures

from observations of the scattered lines (also see Sazonov & Sunyaev 2000).

3 BROADENING OF THE [OIII] AND [NII]+H α EMISSION LINES IN PERSEUS CLUSTER

The Perseus cluster (also known as Abell 426) is a massive nearby cluster with a redshift of $z = 0.0179$ (comoving distance of 75.3 Mpc). It has a cool core with the H α luminosity¹ of 2.4×10^{42} erg/s (Edge 2001), showing one of the most luminous H α line among the nearby clusters. The H α emission in Perseus cluster extends beyond its central galaxy, NGC 1275, in the form of bright filaments (occurring up to 2' from the centre, see Conselice et al. 2001) which appear to be lifted up by the rising bubbles of hot plasma generated by the central AGN (Churazov et al. 2000, 2001). Prominent H α filaments are also found in other cool core clusters (for e.g., McDonald et al. 2010).

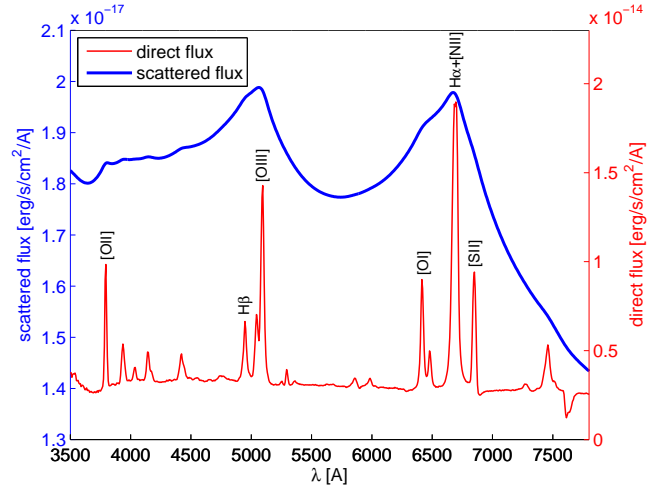
We now estimate the surface brightness and the shape of the spectrum originating from NGC 1275, after scattering by the hot gas surrounding it. The temperature and density variations along the LOS are taken into account (see equation 4) while computing this scattered spectrum; we use the density and temperature profiles from the ACCEPT catalogue (Cavagnolo et al. 2009). The radial Thomson optical depth of the Perseus cluster (estimated by fitting a β model to the ACCEPT data) is $\tau \sim 7.8 \times 10^{-3}$ and its core radius, R_c , is 39 kpc.

Fig. 3 (a) shows the spectrum (in thin red) of NGC 1275 in the wavelength range 3500-7800 Å which was taken by Buttiglione et al. (2009) with the 3.58 m Italian Telescopio Nazionale Galileo over an aperture² of 2''. Some of the prominent lines (with corresponding rest frame vacuum wavelengths in Angstrom) indicated in the spectrum are: [OII] 3727,3730, H β 4863, [OIII] 4960,5008, [OI] 6302, [NII]+H α 6550,6585;6565 and [SII] 6718,6733. The broadened spectrum (in thick blue) is computed by integrating the scattered spectra within a radius $R_{\tau/2} = 50$ kpc, where the radial optical depth drops to 50% of its total value. Note that the scattered spectrum is much smoother since the contrast between peaks and continuum is decreased after broadening. The total scattered flux is $\tau \sim 10^{-2}$ times smaller than the direct flux.

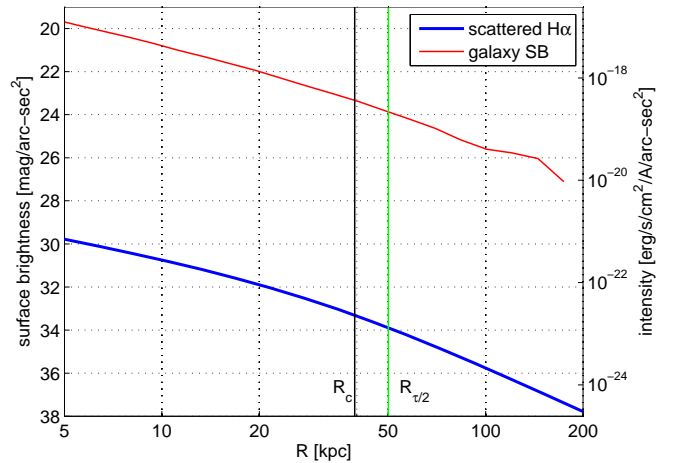
In Fig. 3 (b) the (thick) blue line shows the surface brightness (AB mag/arc-sec²) of the scattered light as a function of the projected distance from the centre of the Perseus cluster. This intensity is estimated near the H α wavelength. Although the plotted line assumes a central point source for the emission, in reality the scattered

¹ The value of luminosity quoted here has been adjusted to comply with a currently accepted value of the Hubble parameter ($h = 0.7$) from $h = 0.5$ assumed in Edge (2001).

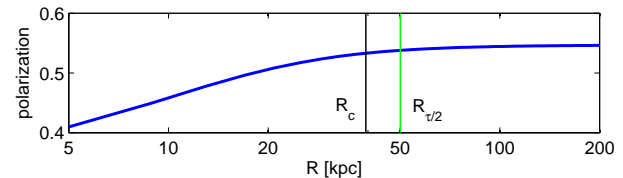
² We estimated (from the available HST images in the H α filter) that the central 2'' region is very bright, containing most of the flux. Including the flux from the outer region would increase this value by at most another $\sim 25\%$. Since an accurately measured flux is available only for the central 2'' and the aim of the paper is to make just a feasibility study, we decided to use this value to estimate the scattered flux.



(a) Scattered and direct spectrum of NGC 1275 (in the observer frame). The left axis in (thick) blue indicates the scattered flux in the thermally broadened spectrum (within a radius $R_{\tau/2} = 50$ kpc), while the right axis in (thin) red shows the intensity of the direct spectrum (from Buttiglione et al. 2009) collected over an aperture of 2''. The colours of the axis correspond to those of the respective spectra.



(b) Surface brightness of the scattered H α emission shown in (thick) blue line as a function of the projected distance R from the cluster centre. The (thin) red line shows the direct (or unscattered) brightness profile (measured at 550 nm, but converted to the observed H α wavelength) of the NGC 1275 stellar continuum from Prestwich et al. 1997. For all the lines in this plot, the left axis indicates the AB magnitude while the right axis shows the corresponding specific intensity.



(c) Expected polarisation of the scattered signal as a function of the projected radius.

Figure 3. Estimate of the expected signal of the diffuse scattered light around the central galaxy NGC 1275 in Perseus cluster.

emission would be flatter on scales comparable to the size of the dominant H α -emitting region. The (*thin*) red line shows the surface brightness of the host galaxy continuum at the observed H α wavelength, estimated³ from Prestwich et al. (1997). It is clear that the host galaxy continuum from the stellar contribution is always expected to be much brighter than the expected signal from scattered light by ~ 10 magnitudes.

Scattering of light from a central source produces a net polarisation at every point such that the direction of the polarisation vector is perpendicular to the radial line joining the given point to the centre (also see Sunyaev 1982). This information about the polarisation of the signal would be useful in separating the contribution from the direct stellar continuum of the galaxy which would be unpolarised. Of course, the stellar continuum would also be scattered and polarised, but this contribution would be fainter by a factor of $\sim \tau$ compared to the direct light. Fig. 3 (c) shows the expected polarisation degree defined as $(I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$, where I_{\perp} and I_{\parallel} are the intensities of the scattered light in planes perpendicular and parallel to the scattering plane.

4 SCATTERING OF THE Ly α AND H α LINES EMITTED BY AN AGN WITHIN A GALAXY CLUSTER

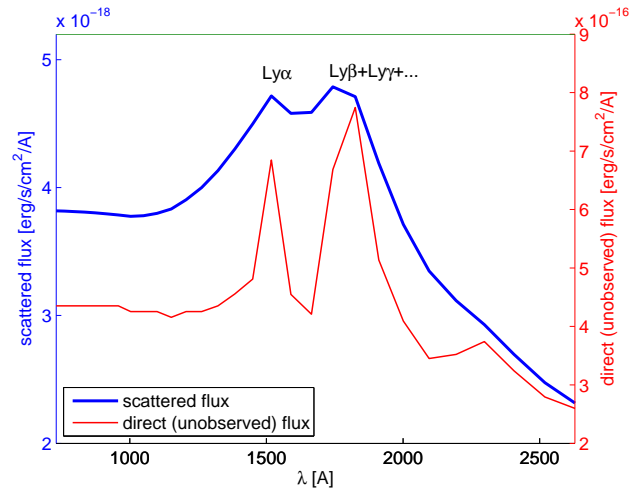
Obviously the diffuse scattered light originating from the H α emission in and around the central galaxy of the Perseus cluster is very faint by itself, and also in comparison with the surface brightness profile of the central galaxy. The detection of such signal is very challenging, at least in the immediate future.

We now discuss an alternate scenario that would allow us to measure the temperature of the cluster ICM using the H α and/or Ly α lines arising from a bright AGN located in the central galaxy. The central galaxies of clusters often have an AGN that emits across a broad range of frequencies from radio to high-energy X-rays, and even Gamma rays, with the presence of several bright emission lines occurring over the entire spectrum.

All AGNs are believed to have common features like a supermassive (10^6 to $10^9 M_{\odot}$) black hole surrounded by an accretion disk and hot corona; the presence of high (inner region) and low (outer region) velocity gas, also referred to as the broad and narrow line regions respectively; and in between these two regions usually lies an optically thick torus of dust and gas. In addition, a relativistic jet originates from within 100 Schwarzschild radius of the black extending upto few 10's of kpc (radio-quiet) to Mpc (radio-loud). According to the unification scheme the different observed properties of AGN, like overall spectral energy distribution and the presence or absence of the broad spectral lines, arise only due to different orientations of the AGN with respect to the observer. If the torus obscures the emission from the broad line region of the AGN it is classified as type II, and otherwise as type I.

³ The conversion of magnitude from 550 nm to the observed H α wavelength was then done assuming that the continuum part of the spectrum is flat and more or less constant in shape. Fig. 3 (a) shows that this is a reasonable assumption.

Figure 4. Scattered and direct spectrum (but hidden from the observer), near the Ly α line, of the AGN in the central galaxy 3C 295 in the observer frame, where the optical depth drops to half its total value. The left axis in blue indicates the scattered flux of the thermally broadened spectrum (within a radius $R_{\tau/2} = 33.5$ kpc), while the right axis in red shows the flux of the direct, but *unobserved* spectrum (estimated from Hopkins et al. 2007). The colours of the axis correspond to those of the respective spectra. The line on the left is Ly α , while the one to the right is Ly β plus other lines in the Ly series.



If the broad-line emission region is hidden from us, as in a type II AGN, and instead we observe only the scattered light, then we could use the information from thermal broadening of the scattered bright emission lines to measure the weighted temperature of the cluster in which the AGN sits. Powerful type II AGNs (radio loud galaxies), especially of the type FR II, sitting within large galaxy clusters would be ideal candidates for making such a measurement. Cygnus A is one such example, being the most luminous nearby AGN, with a bolometric⁴ luminosity of $\sim 3 \times 10^{45}$ erg/s. However it is located close to the galactic plane and hence there would be a strong absorption (HI column density along the line of sight is $\sim 3.5 \times 10^{21} \text{ cm}^{-2}$), especially so for the Ly α line in the scattered emission. Here we consider another powerful AGN sitting in the narrow-line radio galaxy 3C 295 (type II AGN) at a redshift of 0.4605, having a bolometric luminosity (quite similar to Cygnus A) of $\sim 2 \times 10^{45}$ erg/s. This cluster is well suited for our needs as it has a relatively large Thomson optical depth of 1.4×10^{-2} .

Note that the important difference between the two cases discussed is that in the previous section (Perseus cluster) the source of emission is a diffuse region (though small when compared to cluster scale, R_c) while in the present section (3C 295) the emission is from a point source, i.e. the central AGN. For Perseus cluster there is an additional, but small, H α flux arising from the AGN located in the central galaxy NGC 1275, on top of the dominant contribution from the central galaxy and the filaments around it.

We now present estimates of the surface brightness of

⁴ In the template spectrum that we use (to estimate the scattered signal), the line luminosity increases with the bolometric luminosity.

the scattered lines Ly α and H α of the AGN located within a rich cluster of galaxies. The observed hard band (2.0 - 10 keV) X-ray flux of the AGN in 3C 295, corrected for absorption, is 2.1×10^{-13} erg/cm²/s (Allen et al. 2001). This can be converted to an estimate for the bolometric luminosity using equation 19 of Sazonov et al. (2012). Hopkins et al. (2007) provide a code that is used to obtain a template spectra as shown in Fig. 4. In Fig. 5 (a) and (b) we show the scattered intensity/surface brightness near the lines H α and Ly α ⁵. For this we used the observed surface brightness profiles in the g and r bands (Bildfell et al. 2008) and used the average colour-magnitude relations for early-type galaxies from Wu et al. (2005) and Jeong et al. (2009) to estimate the corresponding profiles in the bands relevant to the redshifted Ly α and H α lines. The galaxy surface brightness profiles as shown in the figures are estimated under the assumption that the de Vaucouleurs profile (which is seen to provide a good fit in the r and g bands) holds true across all the filters. However this is only an approximation since the radial colour profiles show a variation of about ~ 1 -2 magnitudes from galaxy to galaxy (see for e.g. Jeong et al. 2009), especially in the outskirts.

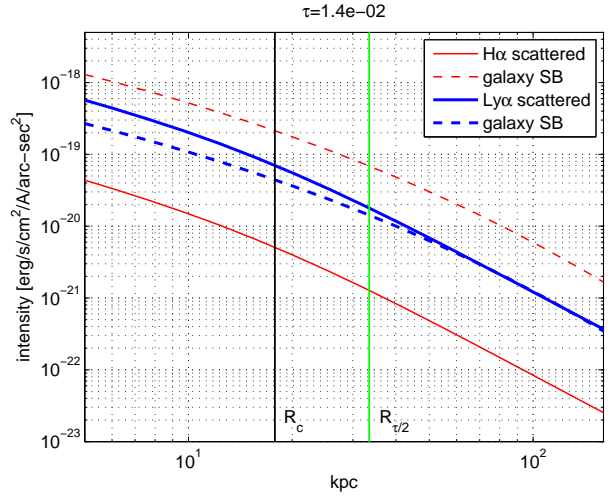
Thus we see that the scattered signal from central AGN in the Ly α and H α lines is expected to be much stronger when compared to the previous case discussed in section 3. In fact the surface brightness of this signal is now comparable to the galaxy brightness, especially so for the Ly α line.

5 FEASIBILITY OF MEASURING THE FAINT AND DIFFUSE SCATTERED SPECTRA

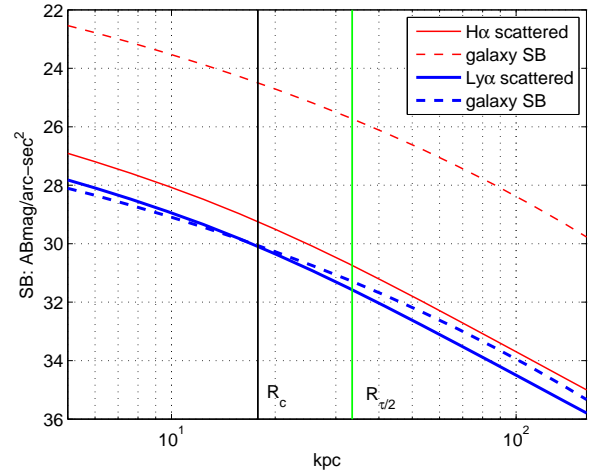
The Thomson scattering emission, at the level of $\tau_T \sim 0.01$ of the direct line flux is smeared out over the region $\sim R_{\tau/2} \sim 20$ –50 kpc and forms a very smooth and faint diffuse component. The surface brightness of this component falls with radius as $I(R) \propto \frac{n_e(R)R}{R^2} \propto n_e(R)/R \propto R^{-\alpha}$, where $\alpha = 1.5 - 2$ over the radial range of interest. Direct imaging of this faint component is extremely challenging. However, one can use the spectral information on broadened lines to separate this component from other components. One possible strategy is to obtain a spectrum averaged over an area (extending typically up to tens of kpc in size), avoiding regions, contaminated by bright filaments and/or the brightest parts of the optical galaxy. Here the fact that the scattered signal is polarised up to $\sim 50\%$ (see Fig. 3 (c)) could also be used to separate the scattered component from the direct component which is expected to be unpolarised.

In recent years there has been significant progress in observing faint diffuse objects. For example, the imaging of intracluster light in Virgo cluster by Mihos et al. (2005) using the 0.6 m Burrell Schmidt Telescope, and follow-on observations where they achieved a surface brightness of $\mu_V \approx 29.2$ (Rudick et al. 2010). Another example is the imaging of the extended stream of stellar debris left over from the tidal disruption of a dwarf satellite galaxy by Martínez-Delgado

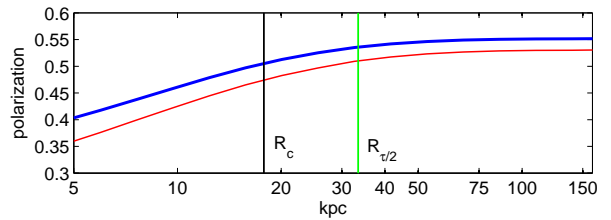
⁵ In the spectrum of 3C 295 we should also directly observe narrow Ly α , Ly β etc. lines with fluxes ~ 1 -10% (as is typical of AGN) of the corresponding (unobserved) broad lines.



(a) Intensity of the scattered H α (*solid thin red line*) and Ly α (*solid thick blue line*) as a function of the projected distance R from the cluster centre. The *dashed* lines in corresponding colours show the surface brightness profiles of the central galaxy 3C 295 estimated at the redshifted wavelength corresponding to the H α /Ly α line.



(b) Surface brightness (ABmag/arc-sec²) of the scattered line of H α (*solid thin red line*) and Ly α (*solid thick blue line*) as a function of the projected distance R from the cluster centre at the surface. The *dashed* lines in corresponding colours show the surface brightness profiles of the central galaxy 3C 295 estimated at the redshifted wavelength corresponding to the H α /Ly α line.



(c) Expected polarisation of the scattered signal as a function of the projected radius for Ly α (*thick blue*) and H α (*thin red*) scattered light.

Figure 5. Estimate of the expected signal of the diffuse scattered light in the galaxy cluster containing the central radio galaxy 3C 295 with a bright AGN. For the above plots R_c and $R_{\tau/2}$ denote the core radius and the distance where the optical depth for the cluster falls to half its value. For this cluster, $1/\tau$ corresponds to 5.8 kpc.

et al. (2008) achieved using the 0.5 m Ritchey-Chretien telescope of the BlackBird Remote Observatory.

In general, the challenges associated with such faint observations are many-fold (see also Duc et al. 2011):

(i) The sky brightness even at the best locations of ground-based telescopes is $\mu_V \approx 21.8$ (for moonless conditions). This is already 2–3 orders of magnitude brighter than the limits reached in above mentioned observations. The sky background must be carefully subtracted, including the effects of background variations, in order to prevent any confusion of the expected signal with the residuals. Of course this will not be an issue for imaging using space telescopes.

(ii) In any CCD detector there are always variations either in the pixel-to-pixel sensitivity or due to distortions in the optical path (e.g. vignetting produced at the periphery). In a perfect flat-fielded image, a uniform source is expected to produce a uniform image. The imaging of extremely faint objects depends crucially on the ability to achieve super-flat fields to be able to distinguish between real features in the image and residual artifacts. A flat-fielding is performed by combining various sky-patches which are slightly offset from the main image.

(iii) For the imaging of extremely faint objects the internal reflections from lenses and other parts of the telescope cannot be neglected. Their contribution can be reduced firstly by baffling of the telescope, keeping the number of optical elements (which act as reflecting surfaces) to the minimum and by using anti-reflective coatings on the optical surfaces to reduce the intensity of the reflections. Secondly, by modelling the complex pattern of internal reflections in software, and then removing them during post-processing analysis (Slater et al. 2009). In this context the use of a closed tube telescope is preferred over the open tube design.

(iv) Some other issues are the presence of halos, and their reflections from internal instrument optics, around bright foreground stars. These halos can be significantly brighter than the low surface-brightness background, which implies that subtraction will not be trivial. Also the presence of galactic cirrus clouds along the line of sight will block and scatter the light from background objects.

Very recently there have been immensely promising results reaching extremely low surface brightness up to 32 mag/arc-sec² (see Abraham & van Dokkum 2014; van Dokkum et al. 2014). This was made possible by the use of multiple commercially available Canon 400 mm f/2.8 IS II telephoto lenses having special anti-reflective coatings that can reduce the effect of scattered light and internal reflections by as much as a factor of 10. By using these small aperture lenses flat-fielding errors can be reduced to less than 0.1%. Secondly, by doing away with secondary mirror assembly the complex and variable pattern of diffraction and ghosting is suppressed. These authors argue that by using a larger grid of multiple lenses, thus giving a larger *effective* aperture, it would be possible to make even further improvements.

Measuring this faint scattered light would certainly benefit from using spatial, spectral and polarisation information (see the beginning of sec. 5) of the signal. The scattered component is expected to have a smooth profile both in wavelength and spatial extent, see Fig. 3. For this rea-

son, neither a high spectral resolution nor highly accurate imaging should be essential (moderate pixel calibration/flat-fielding). In the regions of interest measuring the average scattered light (for example, using stacking) over a small field of view ($\lesssim 1'$) should be adequate. To measure the broadened line widths narrow band (~ 10 – 100 Å) filters or a degraded spectrum from a multi-object spectrograph (MOS), used at wavelengths around the intrinsic bright line, should also suffice. For narrow band filters, absolute flux calibration between the filters used at various wavelengths would be important to measure the shape of the broadened lines accurately. At the same time it would be important to avoid the bright regions and filaments.

Using a very high spatial resolution (~ 10 mas) would further help to exclude pixels containing stars and their halos. Obviously, this (ability to resolve individual stars) seems difficult and could be possible only for nearby galaxies/groups. Here, the sensitivity of the detector must be such that there is no confusion between the stellar light and the thermal noise in the CCD pixels; also the read out noise of the detector must be close to zero.

6 DISCUSSION

Bright emission lines are observed from the central galaxies of cooling flow clusters. The surrounding ICM at temperatures of a few keV with Thomson optical depth of $\sim 10^{-2}$ should scatter the lines causing their broadening of order $\Delta\lambda/\lambda \sim 15\%$. Therefore diffuse scattered light around the central galaxy can be a potential diagnostic of the properties of ICM with regard to electron temperature and density. The ratio of the continuum flux from the direct light to the total⁶ scattered light should give us an estimate of the optical depth of the cluster. The broadening of the bright emission lines can be used to measure the temperatures. The fluxes are very faint and the detection of scattered emission is challenging.

We can also use the scattered lines in Ly α and H α as a probe of the ICM properties in which the central AGN sits. The advantage of this method is that the luminosity of the line is at least 1-2 orders of magnitude higher when compared to the emission from the central galaxies in cooling core clusters. Ly α line is better suited than H α , as it is not only brighter but also the background galaxy surface brightness is much fainter in UV than in IR. The disadvantage is that one would require space based telescopes to observe this signal. In addition the UV detector technology lags behind that in optical. To give a perspective about the sensitivity required of an UV telescope to measure scattered Ly α line in the AGN of the central galaxy 3C 295, it would take ~ 10 million seconds of observation with the ACS/SBC instru-

⁶ Alternatively, one could compute the optical depth as a function of radius by assuming, say a β -model, electron density profile and by measuring the scattered continuum flux within a given aperture at various projected radii.

ment⁷ on the HST. Obviously, new technology is required to be able to measure this faint signal in a reasonable amount of time.

As the scattered lines would be highly broadened the spectra is expected to be extremely smooth. Hence, even observations from multiple narrow-band filters covering the wavelengths of interest should suffice. See for example the ongoing survey J-PAS (Abramo et al. 2012) which would have 42 filters each having a bandwidth of ~ 100 Å starting from the UV band at 3500 Å up to the infra-red band at 10000 Å.

The optimal cluster properties related to measurement of the scattered light would be a large optical depth and the presence of bright (with large equivalent width) emission lines in the central galaxy. It is also preferable to have lower temperatures of the ICM so that the features of the line are not completely washed out due to excessive broadening. Some examples of clusters with these properties are Zw3146 ($z=0.29$), A1835 ($z=0.25$), PKS 745-191 ($z=0.10$), RX J1347.5-1145 ($z=0.45$), RX J1532.9+3021 ($z=0.36$) and SPT-CL J2344-4243 ($z=0.60$). To be able to mask individual pixels having stellar contribution (as outlined in section 5) closer objects are better, since the surface brightness fluctuations decrease with distance. The scattered light should also be visible around large elliptical galaxies, with much sharper features in the scattered lines due to lower temperatures $T_e \sim 1$ keV, although with somewhat smaller (by a factor of ~ 3) optical depth.

The light scattered by the gas in the ICM is polarised and one may in principle use this information to separate the contribution of the direct stellar component which would be unpolarised. However, polarisation measurements of such faint and diffuse light are expected to be highly challenging even with the next-generation instrumentation.

The measurements of optical depths along with X-ray measurements can be used to obtain distances to clusters (Sunyaev 1982; Wise & Sarazin 1990). This is because both these measurements are proportional to the LOS, but weighted differently ($\tau \sim \int n_e dl$ and $S_X \sim \int n_e^2 dl$). Alternatively the width of the broadened lines is $\propto \sqrt{\int T dl / \int dl}$, and can be used to probe the LOS temperature fluctuations, along with a knowledge of the cluster size (using measurements of y and optical depths for example). For optical lines discussed above, the peak of the scattered lines will be Doppler shifted depending on the LOS velocity of the gas at which the scattering occurs and also depending on the relative velocity between the emitting regions and the scattering electrons. This offers a way to probe the transverse motions of gas and to understand the velocity structure in cluster cores (Hatch et al. 2006, 2007; McDonald et al. 2012). Additionally, the proposed method may provide a unique possibility to detect hot intracluster gas around (relatively) distant type II quasars, since such hot gas may be difficult to find in X-rays because of the strong (in X-rays) central AGN and small angular size of the cluster. And finally, the

⁷ This exposure time estimate was derived assuming the F165LP filter and using the online exposure time calculator available at <http://etc.stsci.edu/etc/input/stis/imaging/> for a S/N ratio of 3.0 in the imaging mode with 1×1 pixel for the object diameter of $1''$.

scattered light reaching us would be delayed with respect to the direct emission by $\sim 10^5$ years. Therefore scattered emission reflects mean luminosity of the line over the same time scale.

7 CONCLUSIONS

The main conclusions of this paper are as follows:

(i) The spectra of the central galaxies of clusters often show a few very bright emission lines. The detection of the Thomson scattered line emission by the intracluster gas will open new possibilities to probe the properties of the ICM using UV/optical/IR bands. The width of the broadened lines depends on the electron temperature while the ratio of the scattered light to the direct light probes the electron density (optical depth).

(ii) Due to the large thermal broadening the scattered spectrum would be very smooth. Thus even a very low resolution spectrum or multiple narrow-band filters should suffice. The scattered light needs to be collected from clusters typically within an area corresponding to a few 10 's of kpc in radius from the centre. Depending on the redshift of the object this translates to distances of a few arc-mins to a few arc-secs. Although objects at higher redshifts suffer from low photon count rate and loss of photon energy, the latter might be compensated by the gain in the detector sensitivity at the redshifted wavelengths. For objects at higher redshifts there would not be any disadvantage from having a smaller field of view to measure the integrated scattered light.

(iii) This scattered light from the central galaxies in cool core clusters is expected to be very faint. Measurement of this faint signal needs an accurate understanding of the systematic effects relating to internal reflections in telescopes, flat-fielding and subtraction of sky brightness (for ground based telescopes). This appears to be extremely challenging even with the next generation instruments.

(iv) A more promising prospect seems to be to observe the scattered bright lines like $\text{Ly}\alpha$ and $\text{H}\alpha$ emitted by the central AGN sitting within rich galaxy clusters. The advantage of this method is that now the emission lines from the central AGN are much brighter.

(v) Very recent imaging observations reaching 32 mag/arc-sec² using a grid of commercially available telephoto lenses appear to be highly promising with regards to the ability to reach extremely low-surface brightness, which would be useful for our purpose.

(vi) Since the scattered signal is expected to be very faint, it would be very useful to use the information from the spatial shape, profile and polarisation properties of the scattered component to separate it out from the much brighter direct stellar component.

(vii) Observations of the scattered spectrum can be used to measure distances to clusters, to measure the line-of-sight temperature fluctuations, and to probe the variability of emission from the BCG on time scales of $\sim 10^5$ years.

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