X-Ray Surface Brightness Profiles of Optically Selected Active Galactic Nuclei: Comparison with X-Ray AGNs

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Received 2018 July 16; revised 2018 December 14; accepted 2018 December 18; published 2019 February 7

Abstract

We use data from the All Wavelength Extended Groth Strip International Survey to construct stacked X-ray maps of optically bright active galactic nuclei (AGNs) and an associated control sample of galaxies at high redshift (z ∼ 0.6). From our analysis of the surface brightness profiles obtained from these X-ray maps, we find evidence of feedback from the active nuclei. We find that excluding galaxies and AGNs, residing in group environments, from our samples enhances the significance of our detection. Our results support the tentative findings of Chatterjee et al., who use X-ray-selected AGNs for their analysis. We discuss the implications of these results in the context of quantifying AGN feedback and show that the current method can be used to extract an X-ray source population in high-redshift galaxies.

Key words: quasars: general

1. Introduction

The influence of the central supermassive black hole (SMBH) on the growth and evolution of the host galaxy is evident through a variety of observational and theoretical investigations (e.g., Silk & Rees 1998; Gebhardt et al. 2000; Merritt & Ferrarese 2001; Di Matteo et al. 2005; Peterson & Fabian 2006; McNamara & Nulsen 2007; Chatterjee et al. 2008, 2010, 2015b; Battaglia et al. 2010; Gaspari et al. 2012; Gitti et al. 2012; Pellegrini et al. 2012; Choi et al. 2014). The effect of the central SMBH on large-scale gas and stars in galaxies and clusters is generally known as active galactic nucleus (AGN) feedback in the literature.

The first evidence of interaction between the gas and stars in galaxies and clusters with the central AGN came through pioneering X-ray and radio observations of galaxy clusters (e.g., Nulsen et al. 2005; Dunn & Fabian 2006; Cavagnolo et al. 2011). These pathbreaking observations gave notion to the theory of jet–intracluster medium (ICM) interaction (e.g., Heinz et al. 1998, 2002; Reynolds et al. 2001, 2002, 2005a, 2005b; Choi et al. 2004; Fabian et al. 2005; Vernaleo & Reynolds 2006, 2007; Bogdanović et al. 2009; Tombesi et al. 2015; Yang & Reynolds 2016a, 2016b; Ruszkowski et al. 2017). The jet–ICM interaction was also observed in group environments (Komossa & Böhringer 1999; Zanni et al. 2005; Giodini et al. 2010; Giacintucci et al. 2011; O’Sullivan et al. 2011; Randall et al. 2011, 2015; Vogt et al. 2015). Recently efforts were made by Chatterjee et al. (2015b, hereafter C15) to observe the AGN–ICM/interstellar medium (ISM) interaction in galaxy environments.

Using data from the All Wavelength Extended Groth Strip International Survey (AEGIS; Davis et al. 2007) and the DEEP-2 galaxy redshift survey (Davis et al. 2003; Newman et al. 2013), C15 used AGN and galaxy samples (0.3 ≤ z ≤ 1.3), matched on the basis of their optical properties (e.g., color and redshift), and extracted their X-ray surface brightness profiles. The results were suggestive of an excess in the extended X-ray emission of normal galaxies to that of AGN host galaxies. However, the effect of the Chandra point-spread function (PSF) of the X-ray-bright AGN sample left the conclusion tentative. In this work we follow the same technique as C15 but carry out the analysis with an optically selected sample (Yan et al. 2011) to minimize the effect of the X-ray emission from the AGN itself. Our results support the findings of C15, and we propose that even at galaxy environments we find observational evidence of interaction between the central AGN and large-scale gas in the galaxy.

Our paper is organized as follows. In Section 2 we give a brief description of our data sets and methodology. We present our results in Section 3. Finally, we summarize and discuss our results in Section 4. Throughout the paper we assume a spatially flat, ΛCDM cosmology: Ωm = 0.28, ΩΛ = 0.72, Ωb = 0.04, and h = 0.71 (Spergel et al. 2007).

2. Data Sets and Methodology

We use data products from AEGIS and the DEEP-2 galaxy redshift survey for our analysis.

2.1. Optically Selected AGNs and Galaxy Control Samples

The AGN source data set contains 227 optically selected AGN sources. The optical selection of the AGN is carried out using the [O III]/Hβ line ratio and the U – B rest-frame color (Yan et al. 2011). Out of the total of 291 AGNs, selected via the optical line ratios, 64 of them are X-ray detected (Laird et al. 2009), and the remaining 227 are purely optical AGN candidates with no X-ray counterparts. Typically AGN selection in the nearby universe (z < 0.4) is done using optical emission line ratios of [O III]/Hβ and [N II]/Hα or by their X-ray fluxes. These line ratios are used to classify AGNs and star-forming galaxies in the local universe (e.g., Kewley et al. 2001; Kauffmann et al. 2003) using the BPT diagram (Baldwin et al. 1981), but for higher-redshift sources, the N II and Hα lines redshift out of the optical region into the near-infrared.
Hence, the use of new BPT diagrams with $[O_\text{III}]/H_\beta$ and $U - B$ color has been proposed in the literature (e.g., Yan et al. 2011). The other method of classification that is used for selecting AGNs is the luminosity cut in X-rays ($L_{2-10\text{ keV}} > 10^{42} \text{ erg s}^{-1}$), as no star-forming galaxies in the recent universe are seen to have X-ray brightness higher than this limit (e.g., Ranalli et al. 2003; Yan et al. 2011). Our optically selected sources are reclassified as AGNs by using the X-ray cut. In our sample 76% of the optically selected AGN candidates are not classified as X-ray AGNs (by using the luminosity cut). To confirm that the optically selected and X-ray rejected AGN candidates are not dusty high-redshift star-forming galaxies, the stellar mass distribution of the galaxies is considered. The stellar mass contents of our AGN candidates are found to be identical to the X-ray-selected AGNs, and also they are much more massive than star-forming galaxies (Yan et al. 2011). We note that there might be some AGNs in our sample with lower X-ray luminosities that can appear to be due to lower accretion rates or intrinsic high X-ray absorption of these sources. These sources would not be classified as AGNs according to the criterion of Yan et al. (2011). However, the existence of those undetected X-ray sources will not have any effect on our analysis, because we want to exclude the sources that have been classified as bright X-ray point sources and hence minimize the PSF contamination.

To compare the X-ray environments of our optically selected AGN candidates with those of galaxies, we need to construct an equivalent sample of normal galaxies. To do this, we construct a control sample of galaxies by defining a “matching criterion” using a 3D parameter space involving $B$-band absolute magnitude (proxy for luminosity), $U - B$ color, and redshift with our AGN sample. The normal galaxy control sample contains a total of 5000 galaxies. We want the host galaxies of the AGNs and the control sample to be identical in their properties in order to ensure that whatever impact we see in our analysis comes from the black hole activity and not from the stellar population or other constituents of the host galaxies. See Section 4 for more discussion on this issue. $U - B$ color matching has been done in order to ensure that the AGN host and normal galaxies have similar stellar population and star formation rates (C15). For our analysis, the X-ray-classified AGNs ($L_{2-10\text{ keV}} > 10^{42} \text{ erg s}^{-1}$) and optically classified AGNs are filtered out from the galaxy control sample.

It is also seen in the literature that the galaxy properties depend on redshifts (e.g., Beifiori et al. 2014; Lapi et al. 2014), and hence the samples (AGN and control) are matched in redshift too. Among the 5000 galaxies, 1673 galaxies have single entries only, while 1088 entries have been repeated multiple times in the control sample in order to make the color and redshift distributions of the two samples as similar as possible. The distributions are shown in the left panel of Figure 1. A K-S test ensured a significance $p$-value of 0.97.

### 2.2. Group Catalog

It is known that group environments are likely to affect the extended X-ray emission owing to the enhanced depth of the gravitational potential well. Hence, to identify the group environments associated with the AGNs and galaxies in our sample, we use the DEEP2 group catalog (Gerke et al. 2012). Gerke et al. (2012) used the Voronoi–Delaunay method for finding groups of galaxies in the redshift space. Two or more galaxies are said to belong to a group if they are linked by the group-finding algorithm. Galaxies that are not linked by the group-finding algorithm are denoted as isolated or field galaxies. The catalog enlists the group ID of 34,492 DEEP2 sources, and those having group IDs greater than 10000 are isolated (see Gerke et al. 2012 for details). After eliminating the sources belonging to galaxy groups, we obtain 45 AGNs and 892 galaxy sources from our parent sample. We identified these sources as “isolated.” We also examine the redshift distribution of these two “isolated” samples in order to compare them with the complete sample. The redshift distributions of the samples are shown in the right panel of Figure 1. We perform a K-S test on the redshift distribution of the “isolated” galaxy and AGN samples and obtain a $p$-value of 0.97279, indicating sufficient preservation of similarity. The color distributions of the samples are shown in Figure 2. The K-S test when performed on the color distribution yielded a $p$-value of 0.88275. In
The effective area-exposure-corrected maps of AEGIS-X in our analysis. Table 1 we provide the details of the constructed samples used in our analysis.

### Table 1

Table Showing the Various Cuts Applied to the Initial Sample of 5000 Galaxies and 227 Optically Selected AGNs

| Selection Applied to Sample | Number of AGNs | Number of Galaxies |
|-----------------------------|----------------|-------------------|
| Initial sample              | 227            | 5000              |
| $0.3 \leq z \leq 0.6$       | 80             | 1576              |
| Group catalog               | 45             | 892               |

Note. The sample is reduced to 1576 galaxies and 80 AGNs after the redshift cut. This is our “Complete Sample.” After removing the group-belonging sources, we are left with 45 AGNs and 892 galaxies, which make up our “isolated sample.”

Table 1 we provide the details of the constructed samples used in our analysis.

#### 2.3. Methodology

We follow the stacking analysis technique adopted in C15. The effective area-exposure-corrected (EAEC maps) X-ray maps of AEGIS-X (Laird et al. 2009) have been used for the preparation of the stacked images of our samples. These maps are constructed using the event files, exposure time maps, and effective area maps provided in Laird et al. (2009). A region with dimensions of $5 \times 5$ arcmin has been mapped around each of our identified sources from the EAEC maps. All the other sources present in this region were identified using the AEGIS-X source list, and the getpsf routine provided by Laird et al. (2009) was used to obtain their PSFs. To avoid contamination, the identified X-ray point sources in the mapped region were masked using the ellipse corresponding to 95% of the encircled energy radius (EER; C15, Laird et al. 2009). Circles with radii that are 1.5 times the semimajor axis of these ellipses are assigned zero counts and are placed on the maps with the contaminating point sources at the center of these circles. The conservative circular masks used for each source embed the entire PSF ellipse, and hence the orientation angles of the PSFs do not play a significant role in our analysis.

C15 showed that the surface brightness profiles are statistically invariant if the used mask sizes are 1 or 3 times the 95% EER. A stacked source map is obtained by co-adding these individual source maps. A mask map is prepared accordingly. The pixels other than those falling within the circular masks around the point sources are assigned a value of 1 in the mask map. The mask maps are co-added to obtain a stacked mask map. The final average stacked image is obtained by dividing the stacked source map by the stacked mask map. All the gaps and singularities arising in the EAEC or the stacked maps are assigned null counts. Figure 3 shows the final stacked maps of the AGN and the control sample, respectively. The original dimensions of the stacked maps are of $300'' \times 300''$, but only a $40'' \times 40''$ square region around the center has been shown in Figure 3. Each pixel of the map corresponds to $0.5''$.

#### 3. Results

The stacked maps of each of the two samples (AGN and control samples) have been used to extract the surface brightness profiles of AGNs and galaxies. The average X-ray counts were extracted from the nonoverlapping annuli, each of width 4 arcsec in the stacked maps. The background counts were subtracted accordingly. Figure 4 (top left panel) shows the surface brightness profiles. The blue dot-dashed and red dotted lines show the surface brightness profiles for the galaxy and the AGN, respectively. The error bars represent the standard errors at each annulus. The blue dashed and red solid lines show the average PSF of the galaxy and the AGN, respectively, normalized to the maximum counts in each case. The surface brightness profile of the galaxy clearly shows an excess as compared to that of the AGN.

We note that the Chandra PSF depends on the position of the source in the detector and various other factors and hence would be different for each source. However, since we use an average stacked map for the extraction of the surface brightness profile, we compare our findings with that of the average Chandra PSF at soft X-ray energy following C15. A reasonable estimate of the PSF using the core and the wing is given.
Figure 3. Stacked maps corresponding to the four samples shown in Figures 1 and 2 and Table 1: “complete AGN sample” (leftmost panel), “complete galaxy sample” (second panel), “isolated AGN sample” (third panel), and “isolated galaxy sample” (rightmost panel). The original dimensions of the stacked maps are 300″ × 300″, but only a 40″ × 40″ square region around the center has been shown here. See Section 2.3 for the stacking methodology.

Figure 4. The top left panel shows the extended X-ray count plotted against distance from the center of the complete sample stacked map with 0.3 < z < 0.6 for both AGNs and galaxies. The blue dot-dashed and red dotted lines show the surface brightness profiles for the galaxy and the AGN stacked map, respectively. The green dashed and red solid lines show the PSF of the galaxy and the AGN stacked map, respectively, normalized by the maximum counts in each case. This plot corresponds to the complete sample of AGNs and galaxies as described in Section 2 and Table 1. The top right panel shows the overplot of the surface brightness profile of our complete sample with that obtained by C15, which used X-ray classified AGNs for their analysis. The blue dashed line represents the profile for the current galaxy sample, while the green dot-dashed line represents the galaxy profile for C15. The yellow dotted and red solid lines represent the profiles of the C15 and current AGN samples, respectively. The C15 AGN sample (very high PSF) hugely dominates the C15 galaxy, as well as our AGN and galaxy complete samples. The bottom left panel shows the extended X-ray count plotted against distance from the center of the isolated sources (see Section 2 for description of the sample) stacked map for both AGNs and galaxies overplotted with the complete sample source surface brightness profile. The green dot-dashed and blue dashed lines represent the profiles for the isolated and complete galaxy samples, respectively. The yellow dotted and red solid lines show the profiles for isolated and complete AGNs, respectively. The bottom right panel shows the galaxy count excess from the AGN counts calculated from the surface brightness profiles. For the complete sample the excess is 2.5σ (red), and for isolated sources the galaxy excess is at a significance of 3σ (blue). See Sections 3 and 4 for more details.
by (Gaetz et al. 2004)

\[
f(\theta) = \frac{A_0}{1 + \left(\frac{\theta}{\theta_0}\right)^2} + A_1 \exp \left[-4 \ln(2) \left(\frac{\theta}{\theta_1}\right)^2\right] + A_2 \exp \left[-4 \ln(2) \left(\frac{\theta}{\theta_2}\right)^2\right].
\]

(1)

The fit parameters are taken from C15 and Gaetz et al. (2004).

We stress that modeling the PSF profiles for our stacked maps is a crucial aspect of our analysis, and it is important that the average analytic PSF profile closely mimics the actual PSF profile. Here we follow C15 to test for the differences between the average and the actual PSF profiles. In Section 2.3 we have described our method for obtaining the masks for the X-ray point sources. Using the same method, we constructed a stacked PSF map of our sources. We note that the angular scale corresponding to 1.5 times the 95% EER (the entire PSF profile) varies from 1" to about a maximum of 6" for all the AGN and galaxy sources used in the current work as well as C15. We note that the extent of the wings of the average PSF profiles are larger than the average EER. We further stress that the usage of large circular masks (see Section 2.3) would erase the difference in the axis angles of different source PSFs. We thus conclude that using the average PSF keeps our conclusion unaltered.

In the top right panel of Figure 4 we compare our results with those of C15. The blue dashed line represents the profile for the current galaxy sample, while the green dot-dashed line represents the galaxy profile for C15. The yellow dotted and red solid lines represent the profiles of the C15 and current AGN samples, respectively. The higher emission at the central region for the C15 AGN profile is coming from the bright X-ray emission from the accretion disks of AGNs. It is evident, as has been noted in C15, that the measured X-ray profile of their extended emission is contaminated by the PSF, and the conclusions they draw in their paper are tentative. After correcting for PSF, C15 tend to find that the galaxy count was higher than the AGN count within the error limits. With our new optically selected sources we observe that the excess in galaxy counts is significant compared to AGNs. Our results thus favor the findings of C15.

The stacked maps for the “isolated” samples are also subjected to the same procedure, and the same analytic form of the average PSF is used to produce the X-ray surface brightness profiles of the isolated sources. The profiles are shown in the bottom left panel of Figure 4. We observe that the excess in galaxies over AGNs increases when we exclude sources that are residing in group environments.

Following C15, we obtain the difference profiles between galaxy and AGN. The error in the difference \( \sigma \) is calculated as follows: \( \sigma = \sqrt{\sigma_A^2 + \sigma_G^2} \), where \( \sigma_A \) is the standard error on the mean AGN count and \( \sigma_G \) is the standard error on the mean of the galaxy at the same distance. The results are shown in the bottom right panel of Figure 4. The positive points suggest an excess of the galaxy count over AGN, and negative points suggest an excess of the AGN. The solid blue line represents no difference between the counts. We can see that the galaxy profile shows considerable excess as compared to the AGN.

We also compute the difference for the “isolated” samples using the same statistic described above. We note that the difference increases for the isolated sample when we exclude the AGNs and galaxies residing in groups. The difference profile for the isolated sources has a significance of about 3\( \sigma \), and that of the complete sample shows a significance of about 2.5\( \sigma \). We also removed the group sources from C15 and performed the same analysis. We did not find any significant difference in the case of C15.

4. Discussion

Feedback from the central black hole and its role in galaxy evolution has been widely studied in the literature (e.g., Chatterjee et al. 2015b; Hopkins et al. 2016; Ciolo et al. 2018a; Correa et al. 2018; Penny et al. 2018). The observational effects of AGN feedback have been estimated via many routes, the most recent of which involves the statistical detection of the signal through Sunyaev–Zeldovich observations (e.g., Chatterjee et al. 2010; Ruan et al. 2015; Crichton et al. 2016; Verdier et al. 2016; Dutta Chowdhury & Chatterjee 2017). These large volumes of theoretical and observational studies establish the importance and ubiquity of the role of AGN feedback in theories of structure formation. The direct effects of AGN feedback were seen in cluster and group environments through pioneering X-ray observations proving its global significance at all scales of structure formation.

C15 tried to study the direct effect of AGN feedback on the soft X-ray gas in galaxies, extending the scope of the study to lower-mass structures within the cosmic web. However, as mentioned before, the study of C15 suffered from PSF contamination from X-ray point sources, making their conclusions tentative. The current study aims at improving the conclusion drawn in C15 by replacing the X-ray-selected AGNs with the X-ray dim but optically bright sample of AGNs. In this work, we detect a significant excess X-ray emission from the galaxy stacked maps as compared to the AGN stacked maps, supporting the tentative conclusions of C15.

One of the key assumptions in theories of galaxy evolution is that galaxies reside in dark matter halos (e.g., Silk & Rees 1998). Thus, the extended emission in halos is correlated with the mass of the dark matter halo that provides the gravitational potential well in which the galaxies reside (White & Frenk 1991; Kereš et al. 2005; van de Voort et al. 2011; Correa et al. 2018). Studies show that even the stellar mass in galaxies is correlated with the host dark matter halo mass (e.g., Moster et al. 2010; Shankar et al. 2014; Chiu et al. 2016). Observations suggest that pointed X-ray emission in galaxies too is correlated with stellar luminosity and stellar mass thereof (e.g., Forman et al. 1985; Trinchieri & Fabbiano 1985; Canizares et al. 1987; Sarazin et al. 2000; Strickland et al. 2002; Kim & Fabbiano 2003; Sivakoff et al. 2003; Fabbiano 2006; Ranalli et al. 2008; Mineo et al. 2012). It is believed that the relative contribution to the X-ray emission from the hot halo and the point sources might depend on galaxy luminosity and morphology (see Fabbiano 2006 and references therein).

Thus, to truly understand the X-ray emission in galaxies, one requires a more detailed understanding of the X-ray source population. Chatterjee et al. (2015a) tried to characterize the X-ray source population by using galaxies from the DEEP-2 survey. Their results show that the X-ray emission in high-redshift galaxies (\( z \sim 0.6–0.7 \)) seems to be a combination of point sources and extended emission, and a degeneracy existed between the two classes of X-ray emission. Hence, one of the challenges in studies involving AGN feedback in high-redshift...
galaxies lies in a lack of rigorous quantification of the sources emitting in X-rays.

To alleviate this problem, we have extracted the signal from two kinds of environment, namely, group galaxies and isolated galaxies. It has been shown that group environment and dynamics have effects on the evolution of their member galaxies (e.g., Hou et al. 2013; Roberts & Parker 2017), and the IGM also is affected by the member galaxies (e.g., Helsdon & Ponman 2000, 2003). Hence, we expect the galaxies belonging to the groups to be different from the isolated sources. The group galaxies are themselves a part of the larger gravitational well of the dark matter halo. The diffuse X-ray due to this halo has a large contribution to the X-ray of the member galaxies (Helsdon et al. 2001; Memola et al. 2009). In our study we observe that while including the group galaxies in our stacking analysis provides an excess of the X-ray emission in normal over active galaxies, the significance of this excess increases when we exclude the group galaxies from our AGN and control galaxy samples (as shown in the bottom panels of Figure 4).

This is expected since the diffuse emission in groups in both the AGN and control samples will tend to be identical and will smear out the differences in the average stacked signals. We removed the group-belonging sources from C15 and did not find any difference in the surface brightness profiles from those obtained by C15. This is expected since the PSF emission is large in the case of C15.

We calculate the bolometric luminosities of the optical AGNs according to the methodology described in Marconi et al. (2004) using the B-band magnitude and the redshifts. The bolometric luminosities vary between $10^{43}$ and $10^{44}$ erg s$^{-1}$. The accretion rates are calculated assuming the efficiency of conversion of accreted energy to radiated energy to be 10% (Shakura & Sunyaev 1973). These give accretion rates between 0.01 and $0.17 M_\odot$ yr$^{-1}$. However, we note that the value of 10% is valid for radiatively efficient thin-disk accretion, which is probably not the case in our AGN samples at large. Following the procedure described in Section 4 of C15, we obtain an estimate of feedback energy for our AGN sources.

The feedback energy is found to be $2.1 \times 10^{39}$ erg s$^{-1}$ and $2.3 \times 10^{39}$ erg s$^{-1}$, respectively, for the complete and isolated AGN sources. Thus, according to the current model, the feedback energy is about 0.01%–0.001% of the bolometric luminosity of the AGN.

Now, if we assume the accretion rate energy to bolometric luminosity conversion efficiency to be $\eta$ and the feedback fraction to be $\epsilon$, then the ratio of the feedback energy to that of the accretion energy will be $\eta \epsilon$. Observational studies of wind outflow from quasars find the kinetic luminosity of the outflow to be about 5%–10%, or in some cases 0.01%–1% (Feruglio et al. 2010; Crenshaw & Kraemer 2012; Harrison et al. 2014; Husemann et al. 2016; Revalski et al. 2018) of the bolometric luminosities of these quasars. In the case of radio-loud sources, it has been observed that the kinetic energy of the jet is higher than the bolometric luminosity of the AGN. Thus, the parameter $\eta \epsilon$ in the above cases is higher than our estimates.

Numerical simulations have revealed that the jet couples with the ISM very efficiently (Wagner et al. 2012; Mukherjee et al. 2016), and this efficiency is higher than radiative outflows (Cielo et al. 2018b). Radiative feedback in cosmological simulations has assumed the feedback energy fractions ($\eta \epsilon$) to be typically 0.5% (e.g., Di Matteo et al. 2005; Khandai et al. 2015) of the accreted energy, consistent with our observed values. We stress that these simple estimates are representative, and for more precise comparison we require understanding of accretion models in optically selected lower-luminosity AGNs.

According to current studies, the role of AGN feedback in galaxy formation has been strong. Thus, different observational strategies are being exploited to assess the effect at different scales of structures in the universe. Recently a direct measure of AGN feedback through Sunyaev–Zeldovich observations with the Atacama Large Millimeter Array has been reported (Lacy et al. 2019). We like to stress that our technique to detect this effect at high redshifts, through X-ray observations, is promising (with the limitations of the uncertainty in X-ray source populations). We thus propose to further carry out this study with samples of radio-loud and obscure quasars to validate the evidence of AGN feedback using the X-ray stacking technique.

S.C. acknowledges financial support from the Department of Science and Technology (Govt. of India) for the SERB Early Career Research grant and Presidency University under the entitlement of the Faculty Research and Professional Development Fund. S.C. is grateful to the Inter University Center for Astronomy and Astrophysics (IUCAA) for providing infrastructural and financial support along with local hospitality through the IUCAA-associateship program. S.M. is supported through the INSPIRE fellowship from the Department of Science and Technology, Govt. of India, and the JBNSTS fellowship. S.C. and S.M. thank Arjit Sar for some help with the initial analysis of the work and an anonymous referee for suggesting several clarifications that helped in improving the draft.

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