Asymmetry measures for QSOs and companions\textsuperscript{1}

J.B. Hutchings, C. Proulx
Herzberg Institute of Astrophysics, 5071 West Saanich Rd., Victoria, B.C. V9E 2E7, Canada; john.hutchings@nrc.ca

Received ________________; accepted ________________

\textsuperscript{1}Based on observations obtained with the Canada France Hawaii Telescope, which is operated by CNRS of France, NRC of Canada, and the University of Hawaii
ABSTRACT

An asymmetry index is derived from ellipse-fitting to galaxy images, that gives weight to faint outer features and is not strongly redshift-dependent. These measures are made on a sample of 13 2MASS QSOs and their neighbour galaxies, and a control sample of field galaxies from the same wide-field imaging data. The QSO host galaxy asymmetries correlate well with visual tidal interaction indices previously published. The companion galaxies have somewhat higher asymmetry than the control galaxy sample, and their asymmetry is inversely correlated with distance from the QSO. The distribution of QSO-companion asymmetry indices is different from that for matched control field galaxies at the $\sim 95\%$ significance level. We present the data and discuss this evidence for tidal and other disturbances in the vicinity of QSOs.

Subject headings: galaxies:interactions — galaxies:structure — quasars:general
1. Introduction and data

QSO host galaxies have been associated with tidal disturbances and signatures of merger events, and it appears that such events are often the triggers for nuclear activity (see e.g. reviews by Veilleux 2006 and Hutchings 2006). Investigating red QSOs discovered by 2MASS, Hutchings et al. (2003, 2006) find that these have more pronounced signs of interaction than blue QSOs, and suggest that the red population is in an earlier stage of interaction where associated star-formation produces dust that reddens the active nucleus.

In these investigations, we used visual estimates of interaction level from the images. While these are clearly seen, it is not simple to quantify the interaction signatures. In this paper we introduce and use an asymmetry measure made on the images, which allows us to make more quantitative statements on the galaxies.

In addition to the host galaxies themselves, it has been speculated that neighbouring galaxies may be disturbed, either by outflow or radiation effects from the QSO, or because QSOs are found in environments where there are other merging or interacting galaxies. In this paper we report asymmetry measures on galaxy neighbours of 13 of the 2MASS QSOs in the redshift range 0.3 to 0.6 (from Hutchings et al. 2006). As a control set we have made the same measures on field galaxies of similar magnitude, ‘surrounding’ random stars in the same imaging data as the QSOs. In addition, the asymmetry index was measured for a number of stars in the fields, to provide the zero point for asymmetry for each observation.

The data are described by Hutchings et al. (2006) and are from the CFHT Megaprim camera with the r-band filter. The pixel scale is 0.187 arcsec. Most fields had several exposures, and these were measured individually. Table 1 identifies the QSOs (by their RAs in Hutchings et al. 2006), with some measured quantities. Note that there were 43 companion galaxies in total, but 122 individual measurements were made as the fields were all observed more than once. The control galaxies were selected from the same observations
so that the image quality was matched.

2. Asymmetry index

The most characteristic sign of tidal events or merging in galaxies is asymmetry of the morphology. These events produce faint arms that are seen outside the central galaxy, which in time fall back into the final galaxy configuration, but are visible for periods that probably are longer than a QSO episode. Disk warps and patchy dust may also occur. In the early stages of a merger, the bright central parts of both galaxies may be seen. The common property of all these is that the galaxy does not have symmetrical structure, so that an objective way of measuring a lack of symmetry is a valuable tool in looking for such events. Many such indicators are seen in the faint outer parts of galaxies, so that such a measure should weight these appropriately compared with the bright inner part.

The IRAF task ‘ellipse’ fits ellipses to image data contours, and produces a table of quantities for each ellipse. In particular, for each contour level ellipse, it reports a semi-major axis (SMA) and ellipticity, and deviations from this ellipse in the data. To derive an overall measure of the asymmetry of an object, we want to average these deviations over a range of signal level contours. This average should be weighted in a way that gives the appropriate significance to faint outer features which reveal global asymmetries, compared with the much larger signal from the innermost pixels, which may be more affected by image quality and detector sampling.

Other authors have used an asymmetry measure which is derived from 180° rotation of a galaxy image, subtracted from the original (e.g. Conselice et al 2003, Lotz et al 2004, and references therein). As noted above, we wish to add weight to the faint outer features that are signs of tidal events, rather than flux-weighted asymmetry of a whole galaxy. We also
want a measure that can be compared over different redshifts (i.e. size and flux differences) since we are dealing with a range of redshifts in this work.

After experimentation with a number of recipes, the following was adopted for this investigation: for each contour level, asymmetry = contour signal level x (sum of absolute values of third harmonic deviations from ellipse) x SMA$^{1.5}$. The SMA is measured in units of image pixels. These asymmetry values may be averaged over a range of contours to yield a total asymmetry value for the galaxy. To enable comparison between galaxies with different brightness and size on the sky, this mean value is divided by the total signal in the galaxy. This is to ensure that the same galaxy with an intrinsic asymmetry, will have the same total asymmetry index at different distances (redshifts).

The innermost contours in the ellipse task may be oversampled and also subject to PSF differences and detector saturation. To avoid such effects in the summed asymmetry index, we do not include values for radii less than 5 pixels (about 0.9 arcsec). Far away from the galaxy, the flux falls and the index may be affected by noise, bright pixels, or small unrelated objects in the line of sight. Thus we do not use contours that lie beyond where the contour flux falls below 10% of the average contour level signal to that radius value.

It is of course necessary to edit out stars or hot pixels that do not belong to the object. Accurate sky-subtraction is important for this measure, so that the asymmetry index eventually approaches zero far from the galaxy centre. To compare between different galaxies, the ellipse contour sampling should be done using the same radius steps in pixels, and the numbers normalised to the total signal value as noted above. Radial scaling is not done as the weighting by radius makes the effect of different redshift small. Thus, to compare galaxies with this index, we do not need to know their redshifts.

Figure 1 shows the effect of moving a galaxy to higher redshifts. This shrinks the image linearly with redshift and reduces the signal level by the inverse square of the redshift,
for the low redshift range of interest. The plot shows the contour asymmetry values with scaled radius, after normalising to the total signal, at double and triple the redshift. The asymmetry and its variation with radius are all very similar for the three plots, so that we may compare asymmetry values meaningfully over the range of redshifts of interest in the sample. This type of plot of individual contour asymmetry with ellipse semi-major-axis, also shows where the principal asymmetries lie within the galaxy.

Another potential measure of asymmetry in faint outer parts of a galaxy is the wandering of the ellipse centroids as the SMA increases. We looked at the standard deviation of the centroid coordinates for an image as the simplest way to code this, but it had no correlation at all with the asymmetry measure above, or with the visual index from Hutchings et al (2003,2006). Perhaps a more complex measure of systematic centroid wandering, weighted by contour signal, would be better, but this approach was not explored any further, since the above formula works well, and correlates well with the visual estimates of asymmetry in our earlier paper on the same objects.

3. Measurements

Measurements of asymmetry as described above were made on the program QSOs and galaxies near to them. Galaxies comparable with or fainter than the QSO were measured, out to a radial distance of \(\sim 320\) pixels (1 arcmin). A number of stars were also measured as controls for the low limits for asymmetry from each image, and for the consistency of sky-subtraction. In view of the range of image quality and depth we do not claim to have a complete sample to faint limits, and this forms part of the discussion below.

The main control sample was to measure a similar ensemble of galaxies ‘surrounding’ randomly selected stars in the same images, of brightness similar to the QSOs. Their
distances from the central star were recorded and this sample extended to about 450 pixels. Noting the difference in the QSO companions and control galaxies, it is likely that there are more galaxies around QSOs than around a random place in the sky.

To compare with the observations, we constructed a simple model in which the mean asymmetry index varies from 0 to 200 linearly with distance from a QSO in the range 0 to 400Kpc, with a spread of about 50. This was sampled with points roughly as the volume of space defined by the separation, and with several random realisations of projections on the plane of the sky. We discuss the comparison below.

We also made a model table with asymmetry indices and distances having the same spreads as the QSO companion measures. From this table we generated many randomised distributions of asymmetry with distance, to compare with the measured distribution. This too is discussed below.

Table 2 shows mean asymmetry indices for the different classes of object in this work, including the model outlined above.

In comparing the QSO asymmetries with those of the galaxies, we note that the QSO total signals include the bright nuclei, so these should be removed in comparing the flux-normalised asymmetry indices, as in Table 2. The nuclear to host ratios for the QSOs in the sample are taken from Hutchings et al (2006), and reduce the total fluxes by an average factor 5. These host galaxy fluxes are still several times brighter than their average companion galaxies, and 50% brighter than the brightest. The comparison between the galaxy companions and control galaxy samples are more robust, since they do not contain bright AGN, and are the main interest of the discussion below.

The asymmetry indices for all the QSOs were derived independently by the two authors. Hutchings et al (2006) published ‘interaction indices’ for the QSOs, based on visual
inspection of the images for signs of tidal disturbances. Indeed, the visible appearance of interacting galaxies was used in developing the asymmetry index. Figure 2 shows the comparison of the asymmetry values from both the authors, plotted against the interaction index. In deriving the asymmetry values, each of us derived the sky subtraction and decided on editing of bad pixels etc, independently. The agreement between the two sets of values indicates the level of spread or uncertainty that we should attach to them. The good general correlation with the interaction index also indicates that we have a useable objective measure of tidal disturbance. The values plotted in Figure 2 are the mean asymmetry indices without correction for the total and nuclear fluxes, so are higher than those for the galaxies. As the nuclear fluxes are variable and not well defined, such corrections add extra scatter to the plot, although the correlation with visual interaction index is still clear.

The dots in Fig 2 are the author (CP) measures used for all other objects in this paper. They show a higher spread than the other (JBH) QSO measures but the QSOs are the most difficult objects to measure because of the high nuclear flux in many of them. The overall spread with interaction index indicates that the measure does miss some of the visual signs of tidal disturbance (or possibly that the visual signs are overinterpreted).

One of the QSOs is at much higher redshift (2.37), so that we do not expect to detect companions or measure their morphology at the same level as the others, since they would be several magnitudes fainter. We have excluded it from the discussion below, but it is useful as a further control on the main results. The QSO has very low asymmetry index and so do most of its ‘companions’.
4. Discussion

Figure 3 shows the asymmetry measure plotted against image quality, redshift, and distance from an arbitrary ‘central’ star for the control sample. None of these shows a strong correlation, envelope, or dependence. High values of the asymmetry measure are seen more in better image conditions (top panel) so we looked at these separately to see if any indications are different. In practice, excluding the 23 galaxy measures with FWHM above 1.1” does not alter the distribution of the asymmetry measures with separation from the QSOs. There no indication that asymmetry is lower in the higher redshift object companions (panel 2), but we note that since these are line of sight companions, more may not have the QSO redshift in the higher redshift cases. Nevertheless, eliminating the higher redshift objects does not change the distribution of companion galaxy properties with projected distance from the QSOs.

Figure 4 shows the distribution of nearby galaxy asymmetries with projected distance from the QSOs, in the top panel. This distribution is characterised by an upper envelope that drops with increasing distance from the QSO. The distances are converted to Kpc using $H_0=75$. The figure shows the full set of measures for all the observations. The smaller dots represent 1/3 of the points that are matched in asymmetry distribution with the control galaxy sample, as possible elimination of line of sight companions that are not associated with the QSO. We discuss below the differences in these distributions. Table 2 shows the mean properties of these as ‘decontaminated’. There are no companions brighter than the host galaxy of the QSOs (see Hutchings et al 2006). As noted, the distribution is not significantly altered by eliminating QSO fields with redshift about 0.4, or data with FWHM less than 1.2 arcsec, as noted in the discussion of Fig 3.

In Figure 4 we also compare the measures with the simple model described in the section above. The true distribution is shown in the centre panel, and the combination of 5
random realisations of projection angles is shown in the bottom panel. The model assumes that we have sampled all galaxies evenly by volume of space, out to about 200Kpc and then more sparsely beyond that. This corresponds with what we did measure - we have not measured all of the galaxies in the outer parts of the distribution because of image defects or overlaps. We have consistently measured galaxies down to the same flux limits, in both QSO and control fields, at all distances from the central QSO or star. It is also clear from Figs 3 and 4 that we find no galaxies with large interaction indices at large distances from the QSO, while this is not so for the control galaxies.

Overall, the data are very consistent with the model, and thus suggestive that there may be some disturbing effect of the QSO on nearby galaxies, or that QSOs are associated with tidal events in fairly dense groups of galaxies.

We may compare the asymmetries of the control galaxies to see if they differ from the QSO companions. Looking at the distribution of asymmetry values, the K-S test indicates that they are from different populations at the 91% probability level. If we restrict the control sample to having matched pixel distances or magnitudes to the companions sample, this value goes to 92% and 93%, respectively. Finally, if we compare the companion galaxies with 1/3 removed as line of sight superposed field galaxies with the same distribution as the control galaxy asymmetries (Fig 4 top panel and Table 2), the distributions are different at the 95% level. If the non-companion fraction is higher than 1/3, the probability of them being different populations is still higher. These numbers thus also support the idea that the QSO companions are more disturbed than field galaxies with similar magnitudes.

We also compared the mean asymmetry values for QSO companions with those for the control galaxies, in distance bins of 50 pixels. The QSO companion asymmetries are larger than the controls, at all radii, but differ most significantly in the 50-100 radius pixel bin. The averages are 125 for the QSO companions and 68 for the control sample. If we
decontaminate the companions with 1/3 having the properties of the control group, the mean value for the companions rises to 149, and the difference becomes 3.1 times its formal uncertainty. These and other numbers are given in Table 2.

Finally, from many random combinations of the distributions of distance and asymmetry, we find less than 5% cases with the falling distribution seen in the top panel of fig 4. Thus the envelope of asymmetry with distance as observed is very unlikely to be a chance occurrence.

The density of companion galaxies measured around QSOs is quite high. We measured galaxies that are down to 10% of the QSO host galaxy average. This is an absolute R magnitude in the range -21.6 to -19.1, so we are measuring companions down to the luminosity of the LMC. This galaxy density amounts to 0.3 within 50Kpc, 1.6 within 100Kpc, 2.8 within 200Kpc, and 3.6 within 400Kpc, assuming that all are associated with the QSO. The counts are less complete beyond about 200Kpc, but these numbers are more dense than the local group. The control galaxy counts were not intended to be complete, although areas of sky rich in galaxies were chosen for convenience. Even so, the density of galaxies in the control sample is several times lower than around the QSOs. In such dense groups, tidal interactions are likely to be common, again supporting the finding that the asymmetry is higher close to the QSOs.

Further work on this would include colour information on the galaxies, to see if there is a difference in stellar population age, or dust in the QSO companions. The apparent finding that the companions are most disturbed nearest the QSO suggests that either the QSOs reside in the central (and brightest) galaxy of a group, or that the QSO is causing the disturbances we measure in their companions. Given that these are red QSOs, which are obscured and likely to be new, the former of these seems the more likely scenario.

We thank the referee for helpful comments.
REFERENCES

Conselice C., Bershady M., Dickinson M., Papovich C., 2003, AJ, 126, 1183

Hutchings J.B., Maddox N., Cutri R.M., Nelson B.O., 2003, AJ, 126, 63

Hutchings J.B., 2006, New Astronomy reviews, 50, 685

Hutchings J.B., Cherniawsky A., Cutri R.M., Nelson B.O., 2006, AJ, 131, 680

Lotz J.M., Primack J., Madau P., 2004, AJ, 128, 163

Veilleux S., 2006, New Astronomy reviews, 50, 701

This manuscript was prepared with the AAS \LaTeX{} macros v4.0.
Captions to Figures

Fig. 1.— Asymmetry index with radius for a well-resolved asymmetric barred spiral galaxy (solid line). The innermost values, which oversample the bright nuclear regions, are not plotted. The galaxy has been artificially removed to 2 and 3 times the distance by reducing the signal and pixel binning (dotted and dashed lines respectively). The asymmetry index is relatively free of redshift systematics.

Fig. 2.— QSO asymmetry measures and visual interaction indices from Hutchings et al (2006). The dots are the measures made in this work and the circles are measures made earlier and independently by one of us (JH) on the whole Hutchings et al (2006) sample. The line connects the mean values for each index value. The values are not scaled to the mean flux of the sample galaxies or by the estimates of the nuclear flux, in order to show only the agreement between the independent sets of measures, and the correlation with the visual interaction index.

Fig. 3.— Asymmetry measures which may reveal biases. Top: QSO companion (dots) galaxies and control (circles) galaxies with image quality. Middle: Companion galaxies (dots) and total-flux corrected QSOs (stars) with redshift of the QSO. Bottom: Control galaxies with distance from arbitrarily chosen central star.

Fig. 4.— Distribution of asymmetry measures with projected distance from QSO. Top: measured program objects. Small dots are those that would disappear if 1/3 of them are not associated with the QSO and have the asymmetry distribution of the control galaxies in Figure 3. Middle: model with asymmetry correlated with distance from QSO, as sampled. Bottom: 5 realisations of random projections of the model from the middle panel. The similar distributions in the top and bottom panels show the data are consistent with the model.
Table 1. Summary of sample objects

| Name | #obs | z   | r-mag | #galaxies | Galaxy mags | FWHM' |
|------|------|-----|-------|-----------|-------------|-------|
| 1332 | 2    | 0.346 | 17.1  | 3         | 21.3-22.1   | 0.86-1.01 |
| 1432 | 2    | 0.349 | 16.0  | 3         | 20.9-21.4   | 0.82-0.84 |
| 1435 | 2    | 0.305 | 16.3  | 3         | 20.9-21.4   | 0.90-0.95 |
| 1442 | 2    | 0.307 | 17.1  | 4         | 20.3-21.8   | 0.86-0.92 |
| 1450 | 4    | 0.358 | 17.0  | 3         | 21.1-21.6   | 0.64-0.69 |
| 1501 | 2    | 0.337 | 18.3  | 3         | 21.1-22.1   | 0.90  |
| 1549 | 2    | 2.37  | 17.0  | 3         | 20.2-21.9   | 0.65-0.69 |
| 1550 | 2    | 0.373 | 16.6  | 3         | 19.8-20.3   | 0.64  |
| 1618 | 2    | 0.446 | 18.2  | 3         | 20.3-20.6   | 0.84-0.97 |
| 1644 | 10   | 0.329 | 18.3  | 3         | 20.1-21.1   | 1.2-1.4 |
| 1700 | 4    | 0.596 | 19.7  | 5         | 19.7-21.3   | 1.0-1.1 |
| 1700 | 4    | 0.509 | 16.7  | 4         | 18.3-20.8   | 0.73-0.79 |
| 1715 | 2    | 0.524 | 19.8  | 3         | 21.8-22.2   | 0.80-0.86 |
Table 2. Mean properties of program objects

| Objects                     | Number | Mean asymmetry | Av r-mag | Mean sep in Kpc |
|-----------------------------|--------|----------------|---------|-----------------|
| 13 QSOs                     | 42     | 17             | 17.3    | 0               |
| QSO hosts                   | –      | 85             | 18.8    | 0               |
| Comp galaxies               | 122    | 81             | 20.5    | 141             |
| Comp decontaminated         | 84     | 89             | 20.9    | 138             |
| Comp decont 50-100 px radius| 10     | 149            | 21.3    | 56              |
| PSF stars                   | 105    | 9              | 17.7    | –               |
| Control galaxies            | 136    | 74             | 21.0    | (130)           |
| Control galx 50-100 px radius| 9      | 68             | 21.0    | (58)            |
| Model                       | 20     | 78             | –       | 150             |
