Mid-Infrared Imaging of the Einstein Cross QSO

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Abstract

Observations of the Einstein Cross QSO reveal that the mid-infrared region is unaffected by microlensing. Thus, the infrared emission region must be extended on a scale $> 10^{17}$cm, ruling out synchrotron models, but consistent with dust emission models. Other constraints rule out starburst models. The flux ratios greatly constrain the lens model.

Keywords: quasars: individual (Q2237+0305), gravitational lensing, radiation mechanisms: general, infrared: general

1 Motivation

The spectral-energy distributions of quasi-stellar objects (QSOs) generally show a change in spectral slope near 1 micron, which is indicative that a different emission mechanism operates longward of this wavelength. The spectrum typically peaks at 10-100 microns; the origin of this infrared bump is still in question. One candidate mechanism is thermal dust emission by dust surrounding the QSO which absorbs and reradiates the QSO light. The evidence is the constancy in wavelength of the dip near 1 micron (Neugebauer et al. 1987, Sanders et al. 1989), which may be attributed to the dust sublimation temperature, ~ 1800K. In a few Seyfert 1 galaxies (the nearby, lower- luminosity nieces of QSOs), reverberation studies between the optical and infrared indicate that the infrared lags the dust by several light months, which supports the dust model (Barvainis 1992, Nelson 1996). An alternative model is emission by self-absorbed synchrotron radiation from electrons. The evidence in favor of synchrotron emission is the lack of silicate features which are expected from dust emission and the in-phase infrared/optical variability in some radio-quiet QSOs, which indicates the optical and infrared emission regions are not distinct (Neugebauer & Matthews 1999).

2 Microlensing in the Einstein Cross

One way to distinguish dust from synchrotron is to try to measure the size of the infrared emission region as dust emission has a low brightness temperature, $\sim 10^3$K, while synchrotron has a high brightness temperature, $> 10^8$ K. The dust size is estimated to be

$$R_{\rm dust} = 3 \times 10^{18} \left(\frac{L}{2 \times 10^{46}{\rm erg/s}}\right)^{1/2} \left(\frac{T_s}{1800{\rm K}}\right)^2 \left(\frac{\epsilon}{0.1}\right)^{-1/2} {\rm cm}, \tag{1}$$

where L is the QSO luminosity, T_s is the dust sublimation temperature, and ϵ is the dust emissivity. The synchrotron source size is estimated as

$$R_{\rm synch} \sim 10^{14} h^{-1} \left(\frac{F_\nu}{1{\rm mJy}}\right)^{1/2} \left(\frac{B}{1{\rm G}}\right)^{1/4} \left(\frac{\lambda}{100\mu{\rm m}}\right)^{5/4} {\rm cm}, \tag{2}$$

where F is the flux at the self-absorption turnover frequency λ, and B is the magnetic field strength.

The Einstein Cross QSO, 2237+0305, provides an astronomical laboratory for measuring the size of the QSO emission region. The optical depth to microlensing is high ~ 0.5 for all images, so the optical images fluctuate continuously and independently. If the source is larger than an Einstein radius

$$R_{\rm E} = 1.1 \times 10^{17} M^{1/2} h^{-1/2} {\rm cm} \tag{3}$$

then the fluctuations will be greatly reduced since the magnification pattern will be smoothed from averaging over the entire source. Conveniently, the Einstein radius divides the size scales of the dust and synchrotron emission models, $R_{dust} > R_E > R_{synch}$, so that if synchrotron is correct, microlensing fluctuations will be observed as in the optical, while if dust is correct, the fluctuations will be negligible.

3 Observations

To monitor the infrared bump requires monitoring at $\lambda > 2.7\mu$m (beyond the 1 micron dip), so we utilized the Long Wavelength Spectrometer on Keck. Observations were taken on 28 July, 1999 and 25-26 September 1999 in the 11.7 and 8.9 μm filters, as reported in Agol et al. (2000), as well as a new observation on 7 November 2000 in the 11.7 μm filter for 65 minutes total time and 28 minutes on source. There was a great improvement in signal-to-noise between 1999 and 2000 due to eliminating pattern noise and increasing observing efficiency. The following table shows the fraction of the total flux contained in each image for the two sets of observations:

Date	λ	A	B	C	D
25-26/9/99	11.7 & 8.9 μm	0.27 +- 0.02	0.30 +- 0.02	0.16 +- 0.02	0.27 +- 0.02
7/11/00	11.7 μm	0.250+-0.015	0.277+-0.015	0.180+-0.015	0.293+-0.015
4/8/99	V-band	0.39	0.11	0.41	0.10

The optical data were take from Wozniak et al. (2000), and corrected for extinction. The analysis of the 1999 data is described in Agol et al. (2000). The 2000 data had Poisson errors since the pattern noise was eliminated.

4 The Infrared Source is Due to Dust

There are several lines of evidence that the infrared emission is extended on a scale greater than an Einstein radius. First, the mid-infrared flux ratios disagree with the (extinction-corrected) optical flux ratios at the 6σ level, which indicates that while microlensing magnifies the optical emission region, the infrared emission region is too large to be affected by microlensing. Second, the infrared image ratios agree with the most complete lens models - the best is the $\lambda = 1$ model of Schmidt, Webster, & Lewis (1995, SWL) which has a $\chi^2 = 8$ for the 1999 data and $\chi^2 = 7$ for the 2000. This can only be true if the infrared source is large enough that the magnification ratios of the images are not changed by microlensing. Finally, simulations suggest $R > 0.2R_E$ at the 3 σ level (Wyithe et al. 2001) based on the 1999 data alone.

Even stronger evidence for extended infrared emission comes from the Y2K data. Between the 1999 and 2000 observations, image C decreased by a factor of two (from 1.49 to 0.76 mJy) in V band (as monitored by OGLE, http://bulge.princeton.edu/˜ ogle/ogle2/huchra.html, Wozniak et al. 2000). The other three optical images remained unchanged between the two observations; however, image A underwent a 30% amplification in between. The story is much different in the infrared: the infrared data taken in 2000 show no significant variation over a one-year timescale. Microlensing simulations convolved with sources of various sizes have been used to compute the probability that the infrared source could remain constant in flux within 10% while the optical flux decreased by a factor of 2 within 0.2 R_E (the approximate distance traversed by the QSO over 1.2 years). This probability is nearly independent of the lens model, since it simply depends on the flux of a single image. Figure 1 shows the probability as a function of infrared source size assuming the SWL model 2. The largest source shown was limited by the size of the microlensing simulation (100 R_E). This plot indicates that $R < R_E$ is ruled out at about 90% confidence, thus ruling out the synchrotron emission model.

Based on these observations, we have strong evidence that synchrotron emission does not contribute to the infrared flux since a synchrotron source should undergo the same microlensing-induced fluctuations as the optical. The infrared emission cannot be due to a reddened starburst as there is no corresponding radio emission and the source is not extended. The alternative we are left with is that the infrared emission is due to QSO light absorbed by dust and then reradiated.

5 The IR Spectral Energy Distribution

The surprising fact is that nearly all of the dust in this QSO is at the sublimation temperature, T$\sim$ 1800K. This is indicated by the SED peak at around 2-3 μm, and sharp decrease towards longer wavelengths (see Agol et al. 2001). There are a handful of other QSOs which show infrared bumps around the same wavelength (Wills 1987); however, in larger samples they appear to be quite rare (Edelson & Malkan 1986, Sanders et al. 1989). The infrared spectrum can be fit with a thin (i.e.

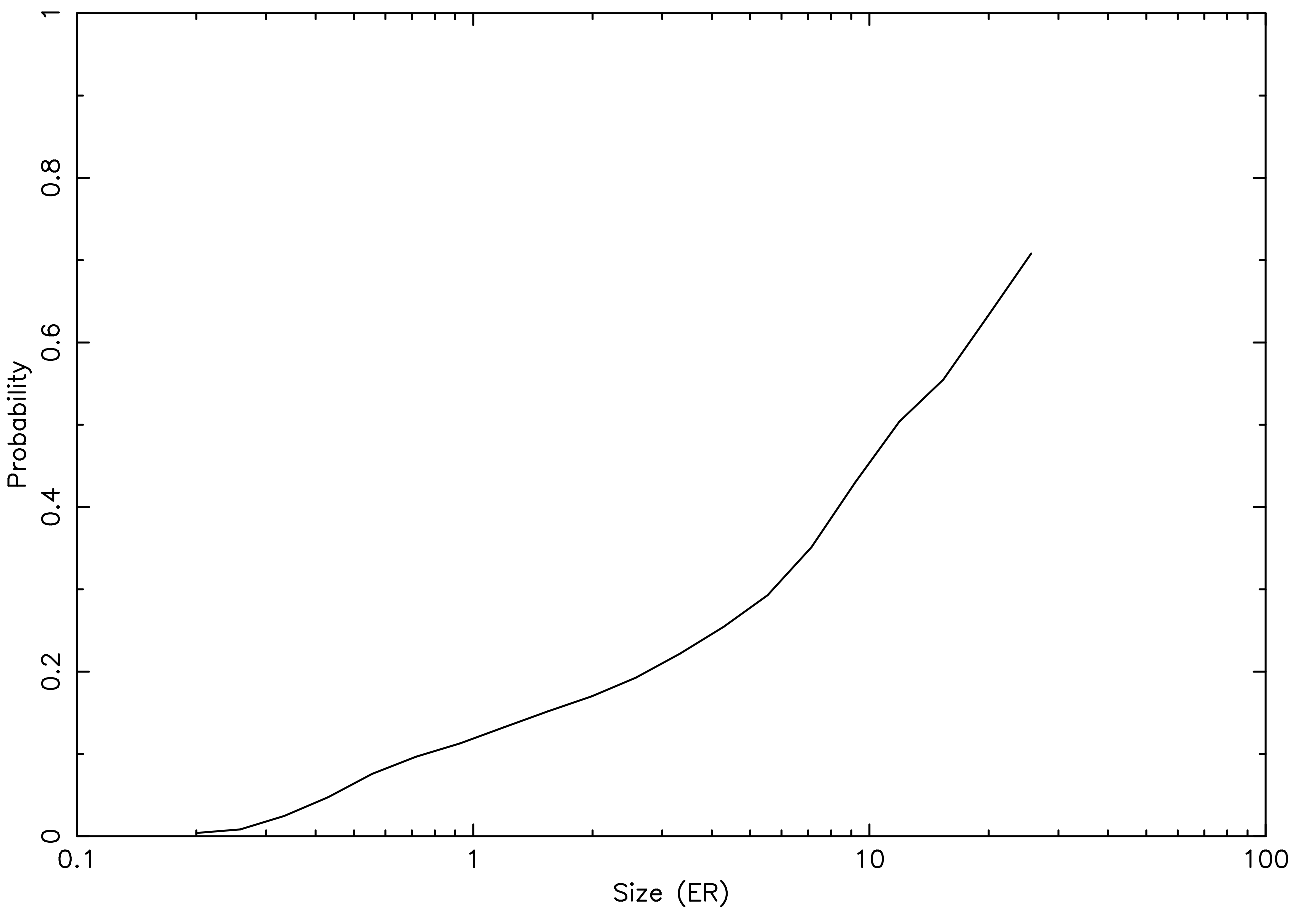

Figure 1: The probability as a function of infrared source size that the IR flux would vary less than observed given the factor of two change in the optical flux of image C. The x-axis shows R in units of the Einstein radius (ER).

dense) shell of dust with the temperature as a function of radius determined by reradiation of the QSO light (which may be absorbed by dust further in). The inner radius, R_{in} is set by the sublimation temperature, while radius at which an optical depth of 3 is reached is at $R_{out} = 3R_{in}$. The covering factor is about 2π. Extrapolated to longer wavelength, the dust spectrum falls well below the millimeter upper limits (Agol et al. 2001).

6 Conclusions

We conclude that the infrared emission in the Einstein Cross QSO is not due to synchrotron, but can be fit with a dust-reprocessing model. Monitoring at shorter wavelengths might reveal the transition from the dust emission region to the optical emission region. The optical/UV SED must be flatter than the $\nu^{1/3}$ prediction of a simple blackbody disk since the dust emission cuts off just above the sublimation temperature, and thus does not modify the optical spectrum. The flux ratios of the four images are most consistent with the SWL model $\lambda = 1$, but better signal-to-noise observations might lead to a better constraint. The infrared SED of the Einstein Cross is unusual, but not unphysical. It is consistent with an archival ISO spectrum, but would be an interesting target for the SIRTF satellite. Observations at 20 μm and 5μm would give better constraints on the dust emission model.

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