Mon. Not. R. Astron. Soc. **348,** L39–L42 (2004) doi:10.1111/j.1365-2966.2004.07563.x

The absence of CO from the dust peak around ϵ Eri

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Accepted 2003 December 18. Received 2003 December 17; in original form 2003 November 13

ABSTRACT

We have searched for the $J = 2$–1 emission of carbon monoxide (CO) from the brightest peak in the epsilon Eridani (ϵ Eri) dust disc – without success. The non-detection sets 3σ upper limits to the mass of CO gas in the dust peak of 3.3×10^{16} kg and to the total amount of (H_2) gas in the disc of 8×10^{19} kg. The paucity of gas in the disc (there is $\sim$1000× more dust) constrains the composition of orbiting comets or icy planetesimals. If these comprise the pre-eminent reservoir of dust and gas in both the Edgeworth–Kuiper Belt (EKB) and the ϵ Eri disc then it seems unlikely that the ϵ Eri planetesimals can be as rich in volatiles as their EKB counterparts.

Key words: Kuiper Belt – circumstellar matter – stars: individual: ϵ Eri.

1 INTRODUCTION

Vega-excess stars are main-sequence stars of moderate age ($\sim$1 Gyr) that maintain dusty discs (Aumann et al. 1984) long after any dust present during the epoch of star and planet formation should have been removed (e.g. Lissauer 1993). Submillimetre images of the dust around the nearest such stars – Vega itself (α Lyrae), Fomalhaut (α Piscis Austrini), β Pictoris and ϵ Eri (Greaves et al. 1998; Holland et al. 1998, 2003) – show discs of sizes comparable to the Sun's Edgeworth–Kuiper Belt (EKB) and with various asymmetric morphologies. These asymmetries have been explained as being due to perturbations by unseen, planetary companions (Liou & Zook 1999; Wyatt et al. 1999; Wyatt 2003). The discs typically contain about 1 lunar mass of dust particles of size 10–100 μm (Dent et al. 2000) which have short lifetimes in the presence of radiation pressure and the Poynting–Robertson effect: as little as 10^4 yr depending upon size and stellar type (Backmann & Paresce 1993). Therefore the dust must be continually replenished, either by the collisional destruction of asteroids or rocky planetesimals (e.g. Zuckerman & Becklin 1993) or by the sublimation (e.g. Harper, Loewenstein & Davidson 1984) of bodies that are more comet-like. The latter process could be expected to supply gas to the disc, depending upon the composition of the parent body. Even for equivalent bodies in our own EKB, however, that composition is not clear (Jewitt & Luu 2000). While no molecular gas emissions have been observed from the nearby Vega-excess archetypes, there *have* been detections from some of the distant, dustier (younger?) members of this class (Coulson, Walther & Dent 1998), and CO *absorption* lines have been seen in ultraviolet spectra of the edge-on disc around β Pic (Vidal-Madjar et al. 1994), where they have been ascribed to infalling comets.

At a distance of $\sim$3 pc, ϵ Eri is one of the nearest Vega-excess stars. Its disc is well resolved in submillimetre imaging (Greaves et al. 1998), and provides a case where the formation and evolution of a debris disc might be studied in detail. In particular, a detection of non-primordial molecular gas could help to define the kind of planetesimals that may exist in its disc.

2 DUST, GAS, PLANETS AND PLANETESIMALS

The ϵ Eri disc is a broken, clumpy ring of radius $\sim$60 au (Greaves et al. 1998). Dynamical simulations of the dust (e.g. Ozernoy et al. 2000) suggest the presence of a planet of mass 0.2 Jupiter masses at the same orbital distance as the ring. A second, more massive ($\sim$1 M_J) planet may also be orbiting the star at $\sim$3 au (Hatzes et al. 2000). The established core accretion theory of planet formation (e.g. Boss 2000) generally allows $\sim 10^8$ yr for the formation of terrestrial planets, but requires gas giants to form within a few million years, before the gas in the primordial solar nebula is lost either by dissipation or by accretion on to – or gravitational clearing by – planets (Lissauer 1993). As with primordial dust, the presence of primordial gas would also, therefore, be unexpected in main-sequence stars of this age, particularly if planet formation occurs much more rapidly, as suggested by revived gravitational instability theories (Pollack et al. 1996; Boss 1997; Mayer et al. 2002).

For a K2 V star like ϵ Eri, classical Poynting–Robertson (P–R) calculations suggest that clearing of primordial dust may take as long as 10^9 yr, which is comparable to its age (Soderblom & Dappen 1989). However, this process may be shortened by grain–grain collisions (Backmann & Paresce 1993; Dent et al. 2000) with clearing actually occurring on time-scales as short as 10^7 yr. Even in the case of a low-luminosity star like ϵ Eri, the observed dust seems unlikely to be primordial.

If the dust is second-generational, and if the parent planetesimals are sufficiently rich in volatiles (comets), then we may expect that the

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continuous resupply of dust to the system may also be accompanied by the resupply of gas, the most easily detectable component of which is carbon monoxide. CO is readily photodissociated even by the interstellar radiation field (van Dishoeck & Black 1988), so a detection of CO in the case of a late-type star like ϵ Eri would confirm a resupply mechanism. A non-detection would put limits on the cometary component of the planetesimal population.

3 EARLIER SEARCHES FOR CO EMISSION

In 1995 we failed to detect CO $J = 3$–2 emission from the ϵ Eri system using a 14 arcsec FWHM beam centred on the star at a 1σ sensitivity of 0.076 K km s^{-1} (Dent et al. 1995). Since then the cold dust in the system has been discovered to lie in a ring of radius ~18 arcsec (Greaves et al. 1998), with only 6 per cent of the continuum emission from the dust emanating from the space within the ring, and ~15 per cent of it emanating from a dust peak in the ring located 19 arcsec east and 8 arcsec south (ESE) of the star. The ring shows two lesser peaks, to the north-east and south-west of the star, and gaps to the north and west. Searches for gas in a system like ϵ Eri should probably avoid the direction towards the star. In Vega-excess systems the gas discs are not always co-spatial with the dust discs (e.g. Dent, Greaves & Coulson 2004) so there is much scope in a resolved system like ϵ Eri to observe in a disadvantageous direction. Searches at positions offset from the star *have* previously been made: locations 40 arcsec from the star were observed (Yamashita et al. 1993) without detection at CO $J = 1$–0 at a 1σ sensitivity of 0.155 K km s^{-1}, while a CO $J =$ 2–1 measure 3 arcsec south of the ESE peak (Greaves et al. 1998) yielded a 3σ limit of 0.025 K km s^{-1}. Our goal in this work was to make a search at a location and to a depth that either would detect CO for the first time in one of the archetype Vega-excess stars, or would severely constrain the amount of gas present. The chosen target direction was towards the strongest of the dust peaks. Since gas and dust in such discs do not necessarily experience the same forces, it is acknowledged that this may still leave potentially more fruitful directions unobserved.

4 OBSERVATIONS

Observations were made using the A-band receiver of the James Clerk Maxwell Telescope (JCMT) tuned to the $J = 2$–1 transition of the CO molecule at 230.538 GHz. The tuning also accommodated the (heliocentric) velocity of the star of +15.5 km s^{-1} so that any features from the target would appear in the centre of the passband. This allowed the use of the highest resolution mode of the Digital Autocorrelation Spectrometer spectrograph (125-MHz bandwidth, 0.07 km s^{-1}). Accounting for the orientation of the disc ($i = 25°$, Greaves et al. 1998), the location of the dust peak within the ring, the orbital velocity of particles located therein (~3.3 km s^{-1}), and the orbital radii covered by the telescope beam, the observed velocity of any emission should be within ~2 km s^{-1} of the systemic velocity of ϵ Eri. In any case the passband covers velocities 90 km s^{-1} either side of systemic.

Observations were made in beam-switched mode, using the secondary mirror to chop against nearby sky at a frequency of 1 Hz. A chop throw of 120 arcsec was used. Samples of 20 min were accumulated in 11 sessions between 2002 August 19 and November 12, with a total on-source integration time of 19 h. The last third of the data were taken with a velocity offset of 11.2 km s^{-1} to allow for the detection of, and correction of, any peculiarities in the DAS detectors. None was seen. The two subsets of data have been merged

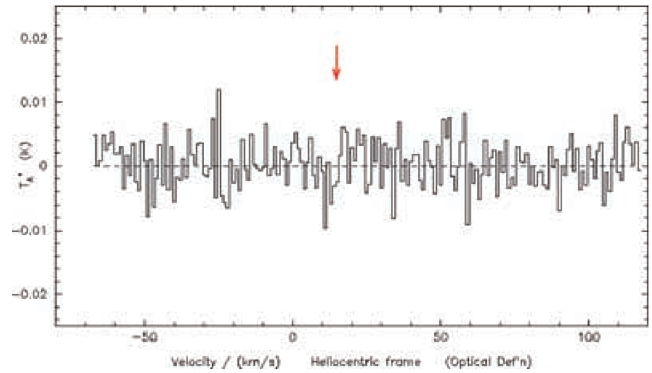

Figure 1. 19 h of integration at the CO $J = 2$–1 line from the ESE peak (19 arcsec east, 8 arcsec south) of the ϵ Eri dust disc. The plot shows antenna temperature T_A^* versus heliocentric velocity. The arrow shows the systemic velocity of the star.

using the SPECX package and are presented in Fig. 1 at a resolution of 1 km s^{-1}. No spectral features are seen, and the 1σ noise in the spectrum at this resolution is 0.0037 K, in units of antenna temperature T_A^*. Conversion to T_{mb} requires division by the main beam efficiency, η_{mb}, of 0.71.

5 THE GAS CONTENT OF THE DISC

Assuming that the gas and dust are thermalized with an equilibrium temperature of 35 K (Dent et al. 2000), the formalism of Knapp et al. (1980) allows the conversion of the observed 3σ upper limit of 0.0156 K km s^{-1} (in units of T_{mb} now) into a column density of CO molecules of 8.7×10^{11} cm^{-2}, implying $<7.3 \times 10^{41}$ CO molecules in the beam. If the emission from the ESE peak fills the JCMT beam, and if this peak holds 15 per cent of all material in the disc (Greaves et al. 1998), then the disc contains a total CO mass of $<2.2 \times 10^{17}$ kg (3σ). Any shielding afforded the CO molecules by dust in the ESE peak will be weaker elsewhere in the disc and must reduce this upper limit even further. If the disc was primordial we could assume a CO:H_2 number ratio for the interstellar medium of 2×10^{-4} and calculate that the disc contains $<2.4 \times 10^{46}$ H_2 molecules of mass $<8 \times 10^{19}$ kg ($<4 \times 10^{-11}$ $M_\odot$). The dust mass in the disc is estimated as 3×10^{-8} $M_\odot$ (~1 Moon mass: Greaves et al. 1998), giving a gas:dust ratio of < 0.001 – a value for a Vega-excess disc as low as any measured previously (Coulson et al. 1998). A CO:H_2 number ratio more appropriate to the break-up of comets or icy planetesimals would be much larger and yield an even smaller gas:dust ratio. The above calculations are fairly insensitive to the exact temperature used, with temperatures in the range 20–60 K changing the derived column density by <50 per cent.

This confirms earlier work (Yamashita et al. 1993; Dent et al. 1995) that discs around Vega-excess stars are very gas-poor compared with the interstellar medium. Either molecular (hydrogen) gas is present and the CO is not a good tracer because of photodissociation by stellar or interstellar ultraviolet radiation (Kamp & Bertoldi 2000), or CO *is* a good tracer and molecular gas is truly depleted in these discs. The lack of CO emissions from the dusty discs around the ultraviolet-bright, A-type, Vega-excess archetypes left this issue unresolved. However, similar, negative results from discs around ultraviolet-weak F, G and K dwarf stars (Greaves, Coulson & Holland 2000) support the latter interpretation. ϵ Eri was one of the systems studied therein, and the current work strengthens the conclusion of that paper. At the location of ϵ Eri the strongest point source of interstellar ultraviolet radiation is Sirius, which is about as distant as it is from the Sun and which contributes less than 1 per cent of the total background ultraviolet flux. The photodissociation rate of CO due to background radiation is therefore essentially identical to that in the solar neighbourhood (van Dishoeck & Black 1988).

The detection of molecular hydrogen gas itself in the β Pic system was recently both claimed (Thi et al. 2001) and disputed (Lecavelier des Etangs et al. 2001). Our new data – an order of magnitude more sensitive to the gas depletion than this latter study – reinforce the conclusion that molecular gas is essentially absent from discs around the archetype Vega-excess stars.

6 DISCUSSION

The mass of CO in the ϵ Eri disc is $<2.2 \times 10^{17}$ kg. The lifetime of CO in the interstellar radiation field is 200 yr (van Dishoeck & Black 1988; stellar photodissociation being minimal in the case of ϵ Eri – Section 5), so the annual rate of CO production is $<1.1 \times 10^{15}$ kg. Assuming that the CO originates in cometary parent bodies and that 10 per cent of cometary material is CO (Delsemme 1985), then the total mass of material added to the disc must be $<1.1 \times 10^{16}$ kg per year. This is <1.6 lunar masses per 10^7 yr (the timescale on which particles are removed from the system: Section 2). The equilibrium amount of cometary gas and dust in the ϵ Eri disc is therefore <1.6 lunar masses (3σ), or $\lesssim 0.5$ lunar masses (1σ). The amount of dust actually detected directly by continuum emission is 1 lunar mass (Greaves et al. 1998). While a signal of CO may be lurking, but not significantly, within our data, we may conclude that the dust observed in the ϵ Eri disc is not likely, at about the 2σ level, to have its origin in comets or icy planetesimals having a Solar system composition.

As in the analyses below, this numerical estimate of probability is based purely on the statistics of the non-detection above, and ignores many systematic uncertainties in our knowledge of the properties of the ϵ Eri material, or indeed of comparable material in our own Solar system.

An alternative indirect estimate of the expected gas mass may be made by comparison of the dust in the ϵ Eri disc with that in the Sun's EKB of planetesimals. Modelling of *COBE* data (Backmann, Dasguptha & Stencil 1995) suggests that the mass of radiating dust in the EKB is 10^{-3} lunar masses (7×10^{19} kg), so the ϵ Eri disc may be viewed in this respect as being 10^3 times dustier than the EKB. With a lifetime for such particles of 10^7 yr (Section 2), this suggests a release rate of dust in the EKB of 7×10^{12} kg yr^{-1} – commensurate with the rates estimated by Jewitt & Luu (2000) and a little less than those estimated by Stern (1996) and Durda & Stern (2000) – and therefore an expected release rate in the ϵ Eri system of 7×10^{15} kg yr^{-1}. If the ϵ Eri system yields CO in the same proportion (10 per cent) as in the EKB then we might expect it to yield 7×10^{14} kg yr^{-1} of CO with an equilibrium mass of 1.4×10^{17} kg: an amount equal to our 2σ observational limit. Again, our observations should have detected CO at about the 2σ level had the physical conditions in the ϵ Eri disc and the characteristics of its component parts (e.g. dust opacities, gas:dust ratios) been similar to those in the EKB. They suggest, instead, and at the same significance level as above, that the ϵ Eri disc is less gassy, i.e. less cometary, than our own EKB.

A third, more direct estimate of CO production in the ϵ Eri system may be made by an extrapolation from the CO sublimation rates from Solar system EKB objects. We adopt as a lower limit a quiescent CO production rate at $\sim$40 au of 10^{22} molecule s^{-1}, as modelled for the 200-km Centaur–Kuiper Belt object (KBO) Pholus (De Sanctis et al. 2000), and assume that the rate is proportional to surface area: i.e. 2×10^{18} molecule s^{-1} km^{-2}. We adopt the size distribution for KBOs by Durda & Stern (2000) and Jewitt, Luu & Trujillo (1998), and assume that all bodies larger than 1 km are sufficiently undifferentiated (De Sanctis et al. 2000) to contribute CO. We compute that the 10^{11} EKB bodies larger than 1 km have a combined surface area of 10^{12} km^2, and would emit 10^5 kg s^{-1} of CO – a figure matched in its entirety by any single 'typical' comet near perihelion (e.g. Hale–Bopp: Jewitt & Matthews 1999). This implies an equilibrium mass of CO in the EKB of 6×10^{14} kg. Again, if the ϵ Eri disc is 10^3 times richer all round than the EKB then we should have detected its CO at the 8σ level.[1]

7 CONCLUSION

The calculations above do not explicitly include collisions as a mechanism for releasing CO into the disc. Collisions will be more frequent and more productive in the relatively young ϵ Eri disc than in the present-day EKB (Stern & Colwell 1997).

Whatever the mechanism(s) that may produce CO in the ϵ Eri disc, the non-detections obtained by this and previous searches provide a limit to the presence of ice-rich comets and planetesimals in the ϵ Eri disc. If the dust observed there is produced by the break-up of EKB-like objects, and if these objects in the ϵ Eri system are otherwise similar to the still rather enigmatic EKB objects, then the observed lack of gas suggests that they have a composition less volatile than that of their EKB counterparts.

ACKNOWLEDGMENTS

The James Clerk Maxwell Telescope is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research and the National Research Council of Canada. The observations were executed by the JCMT Telescope Support Specialists – Jim Hoge, Jonathan Kemp, Thomas Lowe and Ed Lundin – and we thank them for their perseverance and care. We also thank Ben Zuckerman for his comments as referee, particularly for the recognition of possible shielding by dust as a further limit to the amount of gas in the disc.

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[1] Note that differentiation of EKB-like objects increases with age (De Sanctis, Capria & Coradini 2001). While the calculation for the Solar system above was restricted to objects larger than 1 km – to account for the lack of contribution by small, differentiated bodies in a system this old – the small, numerous, less differentiated bodies in the younger ϵ Eri system may still be contributing CO, so the estimated equilibrium mass above must be considered as a lower limit.

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