Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 3 February 1998

A comparison of white dwarf mass estimators using the Intermediate Polar XY Ari

Gavin Ramsay[1], Mark Cropper[1], Coel Hellier[2] & Kinwah Wu[3]
[1] *Mullard Space Science Laboratory, University College London, Holmbury St.Mary, Dorking, Surrey, RH5 6NT*
[2] *Dept of Physics, Keele University, Staffordshire, ST5 5BG*
[3] *Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia*

3 February 1998

ABSTRACT
We determine the mass of the white dwarf in the eclipsing intermediate polar XY Ari following the method given in Cropper, Ramsay & Wu using a multi-temperature bremsstrahlung model. By fitting X-ray spectra from *Ginga*, *RXTE* and *ASCA* we find the mean of the best fits to the data taken using different detectors is M_{wd}=1.28±0.04 $M_\odot$. This figure is too high to be consistent with the mass of the white dwarf found by Hellier from X-ray eclipse timings. There are also small systematic differences between the masses derived using different X-ray satellites.

Key words: Stars: accretion, accretion discs - stars: individual: XY Ari - novae, cataclysmic variables - white dwarfs - X-rays: stars

1 INTRODUCTION

The mass of the white dwarf (M_{wd}) in Cataclysmic Variables is a fundamental property of these binary systems. It is important for binary evolution and is one of the main parameters characterising the emission from the accretion region.

For magnetic Cataclysmic Variables (mCVs), an accretion shock is formed near the surface of the white dwarf and the shock-heated accreting matter emits X rays characterised by the temperature of the accretion shock and the post-shock flow. As the shock temperature depends on the mass of the white dwarf, the X-ray spectra can be used for mass determination (eg Rothschild et al. 1981). Ishida (1991) determined the masses for the white dwarfs in a number of mCVs by fitting to *Ginga* spectra. Cropper, Ramsay & Wu (1998, CRW) took into account the temperature and density structure of the emission region and other additional effects, such as reflection from the white dwarf surface and absorption due to a warm absorber above the emission region, and refined the mass estimates for the 13 mCVs observed using *Ginga*. M_{wd} can also be deduced by fitting X-ray emission lines (Fujimoto & Ishida 1996, Hellier et al. 1996), but there are difficulties for higher M_{wd} (Wu, Cropper & Ramsay 1998). Two mass estimates so far obtained by both the X-ray line and continuum methods are in good agreement (cf Fujimoto & Ishida 1996, Hellier et al. 1996, CRW).

The multi-temperature fitting in CRW promises to be one of the most useful tools for determining M_{wd}. However, the masses they predicted are higher than is generally expected. It is therefore important that the method is cross-checked against other methods of mass determination in order to assess its reliability.

The classical way of determining M_{wd} is to use radial velocities of optical lines, but this method is compromised by a strong dependence on inclination, i. Only in eclipsing systems can we constrain i sufficiently to determine M_{wd}. Even if i is reasonably well-determined, difficulties remain for the mCVs, in which collimated accretion flows dominate the radial velocities. For these systems, an alternative method has been to determine the mass of the secondary star and the mass ratio to infer M_{wd}. The mass of the secondary can be inferred from modelling the infra-red light curves (eg Allan, Hellier & Ramseyer 1996). The main limiting factor for an accurate mass determination using this method is the accuracy of i. In eclipsing systems, determining the radius of the white dwarf gives another excellent method of estimating M_{wd} (Hellier 1997).

Therefore the only hope of cross checking the multi-temperature spectral fits method in CRW is to compare masses determined using it with those determined from an eclipsing mCV. There is no eclipsing polar (synchronous mCV) which is bright in hard X-rays. The only known Intermediate Polar (IP: non-synchronous mCV) with a deep X-ray eclipse is XY Ari. This was observed by Hellier (1997) who determined M_{wd} using an estimate of the radius of the white dwarf from X-ray eclipse timings and by refining the mass estimate of Allan, Hellier & Ramseyer (1996). In this paper, we determine the mass of the system from the *RXTE* PCA, *ASCA* SIS and GIS and *Ginga* LAC data, following the procedure described in CRW. The M_{wd} determined from the three X-ray satellites set are then inter-compared, and contrasted with the mass obtained by Hellier (1997) from X-ray eclipse timings.

2 THE OBSERVATIONS

We briefly describe the data taken using *RXTE*, *Ginga* and *ASCA*. *RXTE* was launched in Dec 1995, its prime aim being to observe sources with maximum time resolution and also with moderate energy resolution. XY Ari was detected in the 2–20keV energy range in observations using *RXTE* between 1996 July 13 and 1996 August 11. It was observed approximately once every day for ~2000sec. The analysis of the X-ray photometry is presented in Hellier (1997) while an outburst (the first to be observed in this source) is presented in Hellier, Mukai & Beardmore (1997). Spectra were extracted for each of the data sections. The mean background-subtracted count rate was 10.4 ct s^{-1}.

The X-ray satellite *Ginga* was launched in 1987 Feb and covered and detected XY Ari in the energy range between ~2–20 keV (see Turner et al 1989 for a review of the instrumentation). XY Ari was observed on a number of occasions using *Ginga*. We extracted a mean LAC spectrum taken in 1989 Jan using the standard software to exclude epochs of high background contamination (these data have been described by Koyama et al 1991). We were left with ~6000 sec of data which had a mean background subtracted count rate of 14 ct s^{-1}.

The X-ray satellite *ASCA* was launched in 1993 Feb and detected XY Ari in the energy range ~1–12keV (see Tanaka, Inoue & Holt 1994). XY Ari was observed using *ASCA* on 1995 Aug 7 for ~34 ksec. The mean count rate in the GIS2, GIS3, SIS0 and SIS1 detectors was 0.094, 0.105, 0.135 and 0.087 s^{-1} respectively.

3 THE RESULTS

We used the multi-temperature thermal bremsstrahlung model (Wu, Chanmugam & Shaviv 1994) as implemented by CRW together with a cold absorber to fit the X-ray data. In the case of the *RXTE* data we simultaneously fitted data taken at slightly different epochs, letting the absorption (N_H) and specific mass accretion rate ($\dot{m}$) vary in the fits. Because of the limitations of the XSPEC package (Arnaud 1996) which was used to fit the data, we had to limit the number of data sets which were simultaneously fit - we therefore made a simultaneous fit to data sections 1–5, 10 & 11 and another simultaneous fit to data sections 12–17 (see Hellier, Mukai & Beardmore 1997). We did not use the data of XY Ari in outburst. For the *ASCA* data we fitted the mean background-subtracted spectra obtained for the GIS detectors and SIS detectors separately and also simultaneously. In the case of *Ginga* we fitted the mean background subtracted *LAC* spectrum.

In fitting the data we restricted the lower energy bound to be ~4keV: this avoided the complications arising from modelling the emission from the region at the base of the post-shock flow where it merges with the photosphere. It also avoided the need for a warm absorber model as used in CRW. An upper energy bound was imposed at the point where the signal-to-noise ratio rapidly decreased (cf Figure 1). This Figure shows the spectra and model fits obtained using *RXTE*, *Ginga* and *ASCA* while Tables 1 and 2 give the resulting M_{wd}, N_H and $\dot{m}$.

Satellite	N_H ($\times10^{22}$ cm^{-2})	$\dot{m}$ (g s^{-1} cm^{-2})	M_{wd} ($M_\odot$)	χ^2_ν (dof)
RXTE				
(1)	0.0–28	0.8–1.5	1.22 (>1.05)	0.96 (202)
(2)	0.0–5.0	0.7–1.5	1.08 (0.86–1.28)	0.81 (203)
ASCA				
(GIS2)	5.3	0.9	1.06 (>0.75)	0.97 (72)
(GIS3)	3.2	0.8	1.27 (>0.77)	0.93 (87)
(GIS2&3)	4.1	0.1	1.37 (>1.15)	0.93 (166)
(SIS0)	6.5	0.9	1.30 (>1.06)	1.02 (59)
(SIS1)	4.5	0.7	1.39 (>1.20)	0.97 (66)
(SIS0&1)	5.4	1.1	1.39 (>1.29)	1.17 (160)
(GIS&SIS)	4.6	1.1	1.40 (>1.33)	0.95 (481)
Ginga	9.4	0.9	1.30 (1.10–1.38)	0.49 (23)
Hellier (1)			0.91–1.29	
Hellier (2)			0.74–1.14	
Refining	1 & 2		0.78–1.03	

Table 1. The best fit parameters for the background-subtracted spectra of XY Ari using *RXTE*, *ASCA* and *Ginga*. (The two *RXTE* fits refer to two sets of data - see text for details). A Fe fluorescence component was fixed at 6.4keV. The best fit values of absorbing column (N_H), specific accretion rate ($\dot{m}$) and mass of the white dwarf (M_{wd}) are shown together with the goodness of fit. The range in the mass is at the 90% confidence level. For comparison, the mass of the white dwarf determined from Hellier (1997) are shown: (1) was obtained from ellipsoidal modelling of the IR light curve and the secondary mass-radius relationship, while (2) was from a study of the X-ray eclipse timings. We also show the mass derived by refining the Hellier (1997) estimates.

We now briefly discuss in more detail some of the parameters in the model fit. The ratio of cyclotron to bremsstrahlung cooling is characterised by the parameter ϵ_o (Wu, Chanmugam & Shaviv 1995, CRW). As cyclotron cooling plays an insignificant role in IPs, this was fixed at the low value of 0.001. By inverting equation 10 of Wu, Chanmugam & Shaviv 1994 we find we have imposed a magnetic field strength of B =1–3MG (depending on the spectrum). The viewing angle to the accretion region is expected to be $> 55^\circ$ for an inclination of $i = 80 - 84^\circ$ and a magnetic dipole offset of 8–27° (Hellier 1997). However, this parameter has a small effect on the fit: varying the viewing angle between 0–90° varies the mass of the white dwarf by only $0.02M_\odot$.

Figure 1 shows the spectra and model fits obtained using *RXTE*, *Ginga* and *ASCA* while Tables 1 and 2 give the resulting M_{wd}, N_H and $\dot{m}$. An Fe fluorescence component from the white dwarf surface (fixed at 6.4keV) is included for the results in Table 1 but not for Table 2 (thermal lines, including Fe, are already included in the CRW method). The uncertainty of the masses shown in Tables 1 and 2 were determined by stepping through a range of white dwarf masses and fitting the spectrum as before while all the other free parameters were allowed to vary. The confidence range was

Satellite	N_H ($\times 10^{22}$ cm^{-2})	$\dot{m}$ (g s^{-1} cm^{-2})	M_{wd} ($M_\odot$)	χ^2_ν (dof)
RXTE				
(1)	1–33	0.9–1.6	1.03 (0.94–1.11)	1.00 (216)
(2)	2–6	1.3–1.7	0.95 (0.85–1.05)	0.80 (217)
ASCA				
(GIS2)	7.5	0.9	1.05 (0.82–1.32)	0.82 (74)
(GIS3)	6.7	0.7	1.38 (>1.20)	1.12 (89)
(GIS2&3)	6.8	0.9	1.27 (1.06–1.39)	0.86 (170)
(SIS0)	7.5	0.9	1.29 (>1.00)	1.03 (61)
(SIS1)	5.0	0.7	1.39 (>1.20)	0.97 (68)
(SIS0&1)	6.2	1.1	1.37 (>1.27)	1.21 (164)
(GIS&SIS)	4.8	1.2	1.40 (>1.36)	1.03 (489)
Ginga	9.4	0.9	1.28 (1.12–1.38)	0.45 (25)
Hellier (1)			0.91–1.29	
Hellier (2)			0.74–1.14	
Refining	1 & 2		0.78–1.03	

Table 2. As Table 1, but with no Fe fluorescence component at 6.4keV.

taken at the 90% level ($\Delta\chi^2$=2.71) for this single parameter. The values for N_H and $\dot{m}$ are not well constrained.

The fits to the X-ray data are good ($\chi^2_\nu \sim 1$). The inclusion of an Fe fluorescence line at 6.4keV makes a very small difference to the fitted mass – only in the case of the *RXTE* data does the inclusion of the line make a significant change to M_{wd} (in the sense that the mass increases when we include the line).

4 PREVIOUS MASS DETERMINATIONS

The starting point for the determination of the mass of the white dwarf in XY Ari in Hellier (1997) is a range of inclinations. The lower limit, 80° at 90 per cent confidence, is required to model the IR ellipsoidal lightcurves (Allan, Hellier & Ramseyer 1996). The upper limit of 84° is set by the requirement to see the lower accreting pole of the white dwarf through the inner disc hole carved out by the magnetic field. This is a firm limit unless the interpretation in Hellier, Mukai & Beardmore (1997) that we see the lower pole in quiescence is wrong, or unless the accretion disc is unconventional, such as it is disrupted well outside the corotation radius. The possibility of such a disrupted disc is unlikely, as it is difficult to justify on the grounds of the current understanding of the physics of accretion onto magnetic compact objects.

From the range in inclination, the length of the X-ray eclipse (2050 sec) constrains the mass ratio q to lie between 0.48 (for $i = 84°$) and 0.68 (for $i = 80°$), with negligible error compared to other uncertainties. Hellier (1997) then used eclipse timings to find, for this range of q, a white dwarf radius of 4.3–7.3$\times 10^8$ cm, and hence a white dwarf mass between 0.74 $M_\odot$ (for $q = 0.48$) and 1.14 $M_\odot$ (for q=0.68), (again with the uncertainties dominated by the range in q).⋆

However, we also have an estimate of the secondary star mass of 0.62 $M_\odot$, from Patterson's (1984) secondary-star mass-radius relation and the orbital period of 6.06 hr. This propagates to another constraint on M_{wd} which has the opposite dependence on q to the one described above ($M_{wd} =$ 1.29 $M_\odot$ for $q = 0.48$ to $M_{wd} = 0.91$ $M_\odot$ for $q = 0.68$). Satisfying both constraints simultaneously gives the sole solution of $q = 0.62$ and hence $M_{wd} = 1.00$ $M_\odot$ with an estimated error of only 0.03 $M_\odot$ (90 per cent confidence), although this does not take into account any systematic errors.

Many reports find that secondary stars are less massive than predicted by Patterson's (1984) relationship, and this permits a lighter white dwarf, down to the limit allowed by the eclipse data. However, we can only obtain a heavier white dwarf if the secondary is more massive for its radius than that given by the main-sequence mass-radius relation (something never previously suggested in CVs). If we don't consider the over massive secondary possibility, we then have an upper limit to the white dwarf mass of 1.03 $M_\odot$ and a lower limit of 0.74 $M_\odot$.

5 DISCUSSION AND CONCLUSIONS

Figure 2 shows the results in diagrammatical form. There it is clear that fitting the X-ray spectral data using the method of CRW requires $M_{wd} \gtrsim 1.0 M_\odot$. However, it is also apparent that there are systematic differences between M_{wd} determined from the various satellites. For instance, taking M_{wd} obtained from fits to two or more detectors on *ASCA* we find $M_{wd} = 1.39 \pm 0.01$ $M_\odot$ (1σ). This is higher than that found from the mean of the two *RXTE* points (M_{wd}=1.15±0.07 $M_\odot$). The *ASCA* SIS masses are higher than the *ASCA* GIS results (1.36±0.03 $M_\odot$ compared with 1.23±0.09 $M_\odot$). The best fit to the *Ginga* data ($M_{wd} = 1.30 \pm 0.20$ $M_\odot$) is consistent with the *ASCA* masses.

At this stage it is not clear why there are these differences in the fitted M_{wd} between the various detectors. They could arise from problems in the detector calibration matrices or background subtraction. In fact there is evidence that spectra are systematically softer in *RXTE* compared to that obtained using other satellites (Jahoda, *RXTE* team, private communication). This will lower the effective temperature and hence produce a lower white dwarf mass, helping to explain why we get a lower mass from *RXTE* data compared to the *ASCA* and *Ginga* data. There is an additional uncertainty in the *RXTE* result since for weak sources such as XY Ari the background subtraction is less certain. The value from *ASCA* is likely to be the most reliable due to its much lower background and better spectral resolution.

An alternative may be due to the fact that the *Ginga* and *ASCA* spectra we used were taken over an extended period of time, so that parameters such as N_H or $\dot{m}$ are averages over which a single parameter may be inappropriate. In contrast, the exposure of each section of *RXTE* data was ~2000 sec.

⋆ These masses are slightly lower than in Hellier (1997) since Hellier altered the white dwarf mass-radius relation of Hamada & Salpeter (1961) by 5 per cent following the work of Koester & Schoenberner (1986); this is not done in the method of CRW so is not included here for consistency.

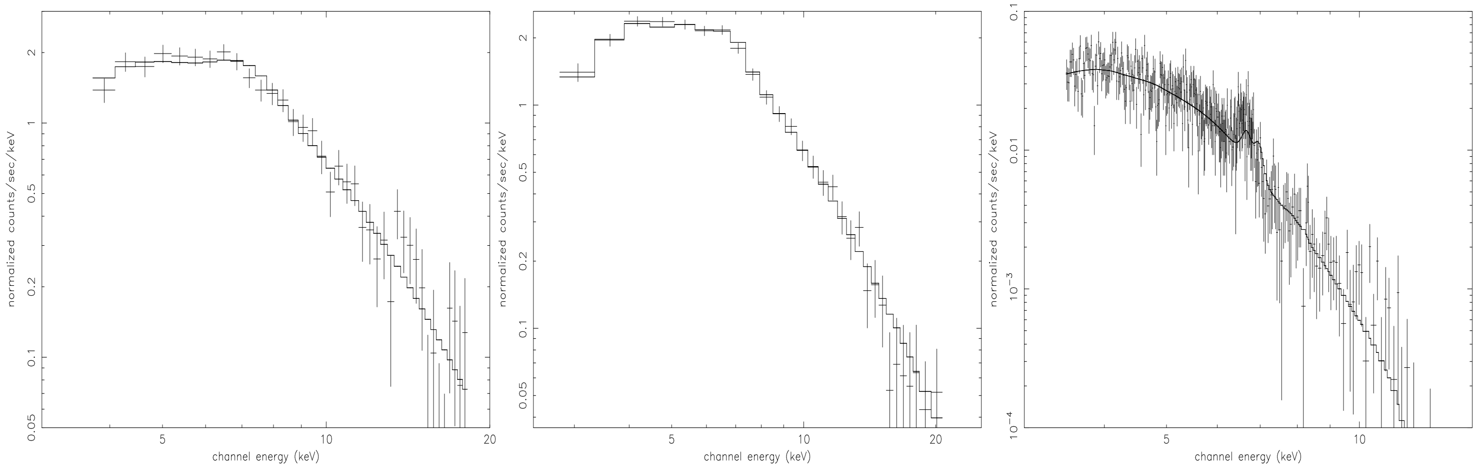

Figure 1. From left to right: The *RXTE* PCA spectrum from the first individual data section, the *Ginga* LAC spectrum and the *ASCA* SIS0 spectrum of XY Ari in quiescence. The best fit of the cold absorber, multi-temperature bremsstrahlung plus a Gaussian fixed at 6.4keV modelling the Fe fluorescence component is also shown.

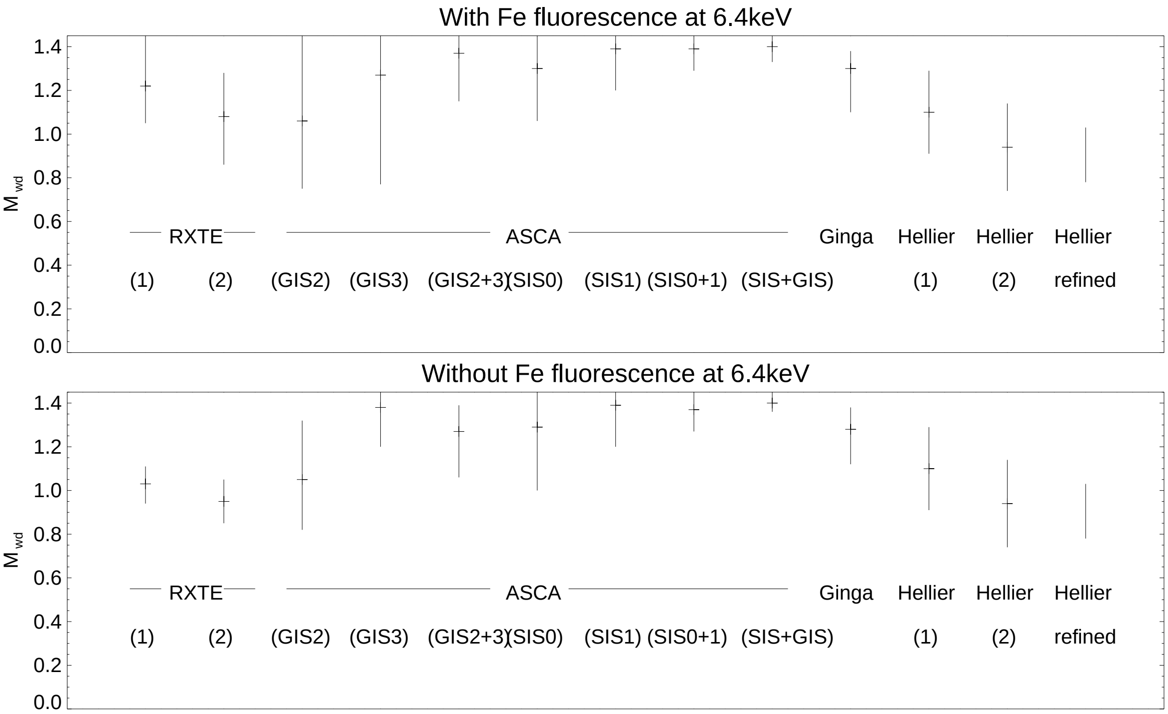

Figure 2. The results of Tables 1 & 2 shown in diagrammatical form.

The systematic differences between fits using different satellites makes taking a simple average problematic, but it is nevertheless instructive. With the Fe fluorescence line included, the mean mass using all our X-ray results is $M_{wd} = 1.28 \pm 0.04\ M_{\odot}$. Without the Fe fluorescence line the values are $M_{wd} = 1.24 \pm 0.05\ M_{\odot}$. These mean masses are not consistent with the mass derived by refining the mass estimates of Hellier (1997) (M_{wd}=0.78–1.03 $M_{\odot}$).

While the differences between the masses deduced from the *RXTE*, *Ginga* and *ASCA* data may be due to the calibration of the detectors, the differences between the masses estimated using the CRW method and results obtained by Hellier (1997), (and refined in this paper), could be due to the assumptions used in the CRW model. For example, the electrons and the ions might have different temperatures and this will cause uncertainty in the shock temperature, and hence M_{wd} determined from the X-ray spectrum. These effects may be important and need further investigation.

The result of this inter-comparison might indicate that there may be some bias towards higher masses in the CRW determinations. Work is in progress at refining some of their assumptions, especially those which are critical for the higher-mass white dwarfs. Nevertheless, because the CRW method is not strongly affected by the orbital inclination, it remains useful in determining M_{wd} in non-eclipsing systems.

6 ACKNOWLEDGEMENTS

We would like to thank the referee for making helpful comments on the first draft of this paper. This allowed us to make substantial improvements to the paper.

REFERENCES

Allan, A., Hellier, C., Ramseyer, T., 1996, MNRAS, 282, 699
Arnaud, K. A., 1996, Astronomical Data Analysis Software and Systems V, ASP Conf Series, 101, 17
Bergeron, P., Saffer, R. A., Liebert, J., 1992, ApJ, 394, 228
Cropper, M., Ramsay, M., Wu, K., 1998, MNRAS, 293, 222 (CRW)
Fujimoto, M., Ishida, M., 1996, ApJ, 474, 774
Hamada, T., Salpeter, E. E., 1961, ApJ, 134, 683
Hellier, C., 1997, MNRAS, 291, 71
Hellier, C., Mukai, K., Ishida, M., Fujimoto, M., 1996, MNRAS, 280, 877
Hellier, C., Mukai, K., Beardmore, A., 1997, MNRAS, 292, 397
Koyama, et al, 1991, ApJ, 377, 240
Patterson, J., 1984, ApJS, 54, 443
Rothschild, R. E., et al 1981, ApJ, 250, 723
Tanaka, Y., Inoue, H. and Holt, S. S., 1994, In 'The X-ray Astronomy Satellite ASCA', PASJ, 46, L37
Turner, M. J. L., et al. 1989, PASJ, 41, 345
Koester, D., Schoenberner, D., 1986, A&A, 154, 125
Wu, K., Chanmugam, G., Shaviv, G., 1994, ApJ, 426, 664
Wu, K., Chanmugam, G., Shaviv, G., 1995, ApJ, 455, 260
Wu, K., Cropper, M., Ramsay, G., 1998, in prep