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DISCOVERY OF AN X-RAY BURST FROM 4U 2129+47

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ABSTRACT

An X-ray burst from the 5.2 hr binary 4U 2129+47 was discovered with the *Einstein Observatory*. The burst appears to be a type 1 X-ray burst, generally interpreted as due to a thermonuclear flash on a neutron star. This discovery resolves any remaining questions as to the nature of the compact object in this source—whether it is a neutron star or a white dwarf—in favor of a neutron star. The peak luminosity is ~ 500 times below the limiting Eddington luminosity, which is often reached in such bursts. The rise time is slower, and peak temperature may be higher than is typical of type 1 bursts. The unusual observed properties of this burst may be used to probe the conditions in the accretion disk corona, or alternatively, given a set of accretion disk corona parameters the intrinsic (before scattering) characteristics of the burst can be derived. We find the former case more interesting and, assuming a reasonable set of burst parameters, conclude that these observations support a model of 4U 2129+47 in which the accretion disk blocks our view of the central source, and the X-rays we detect are scattered off a surrounding accretion disk corona with $T \approx 10^8$ K, $\tau_{es} \lesssim 5$, and $R \approx 4 \times 10^{10}$ cm.

Subject headings: stars: neutron — X-rays: bursts — X-rays: sources

I. INTRODUCTION

The object 4U 2129+47 was discovered as an X-ray source by Forman *et al.* (1978) at a flux level of 10–20 UFU, corresponding to ~ 2.4–4.8 × 10^{-10} ergs cm^{-2} s^{-1} (integrated over 2–10 keV). A precise position determined with the *HEAO 1* Scanning Modulation Collimator allowed identification of V1727 Cygni as the optical counterpart (Thorstensen *et al.* 1979). The optical light curve shows a 5.24 hr periodic modulation with a rounded shape and a V-shaped minimum (McClintock, Remillard, and Margon 1981). The X-ray light curve is modulated with the same period, phase, and approximate shape as the optical light curve (Ulmer *et al.* 1980; McClintock *et al.* 1982).

There remains some uncertainty as to whether the compact component in 4U 2129+47 is a white dwarf or a neutron star, and therefore whether this system is a cataclysmic variable (CV) or a low-mass X-ray binary (LMXB), respectively. While the widely accepted work of McClintock *et al.* (1982) models the system as a LMXB, it cannot rule out all possible CV models. Some of the observations which favor CV models are as follows:

1. The X-ray to optical luminosity ratio of ~ 20 is closer to that usually found in CVs than that found in LMXBs (Patterson 1981).

2. The X-ray light curve is similar to that found in some CVs and has been compared to that of the CV AM Her (Ulmer *et al.* 1980).

3. Most importantly, the recent dynamical mass measurement of the compact component by Horne, Verbunt, and Schneider (1986) of 0.6 ± 0.2 $M_\odot$, which is in the range of those determined for white dwarfs (Shafter 1983; Weidemann 1979), has reopened the discussion on the nature of this system. Since there are theoretical reasons to expect neutron star masses to be ~ 1.4 $M_\odot$, and the observed neutron star masses are clustered around 1.4 $M_\odot$ (Joss and Rappaport 1984), this low mass measurement may imply the compact object is a white dwarf.

Some of the observations which favor the LMXB model are:

1. There is a lack of the very strong emission lines in the optical spectrum which are characteristic of CVs.

2. The X-ray luminosity of $L_x \approx 10^{35}$ ergs s^{-1} (for a distance of 2.2 kpc; McClintock, Remillard, and Margon 1981) is a factor of $\gtrsim 10$ higher than the brightest CVs (Córdova and Mason 1983). For the lowest distance determined to the system (~ 1 kpc; Horne, Verbunt, and Schneider 1986) the X-ray luminosity is still substantially higher than that for CVs.

3. The dynamical mass measurements could be in error (cf. discussion below) if they are affected by unsuspected emission-line variations. In the LMXB model, the V-shaped minimum in the X-ray light curve is interpreted as due to the gradual eclipse of an extended accretion disk corona (ADC) by the companion (McClintock *et al.* 1982), as in 4U 1822−37 (White *et al.* 1981). The optical light curve can then be understood in terms of the varying viewing geometry of the X-ray-heated face of the companion, as in Her X-1.

We have discovered a type 1 burst from 4U 2129+47. Type 1 bursts are distinguished from the type 2 bursts seen in the rapid burster by a gradual softening of the spectrum in the burst decline (Hoffman, Marshall, and Lewin 1978). (For the sake of brevity, we will refer to type 1 bursts simply as bursts hereafter.) An X-ray burst has never been detected from a CV, so on purely phenomenological grounds we infer that the compact component of 4U 2129+47 must be a neutron star. We also use the observed differences between typical bursts and the burst observed from 4U 2129+47 to probe the conditions in the accretion disk corona surrounding this LMXB.

II. OBSERVATIONS

In order to study the variability of the LMXBs, we have been reprocessing the data from the *Einstein* Monitor Proportional Counter (MPC) (Grindlay *et al.* 1980; Gaillardetz *et al.* 1978). The MPC Pulse Height Analysis (PHA) data is recorded in eight pulse height (energy) channels and has 2.56 s time resolution. Higher (~ μs) time resolution data, but no energy resolution and with significant dead time, is provided the Time Interval Processor (TIP) (Weisskopf *et al.* 1981). In the course of our analysis, an X-ray burst from 4U 2129+47 was found. The burst occurred on 1978 December 15 at 22:01:03 UT, which is at phase 0.55 ± 0.09 on the ephemeris of McClintock *et al.* (1982). The average source flux, excluding the burst, during this short (~ 2000 s) observation was ~ 1.0×10^{-10} ergs cm^{-2} s^{-1} from 2 to 10 keV. This flux level is substantially lower than that reported in the 4U catalog (Forman *et al.* 1978) but comparable to that observed in 1980 June (McClintock *et al.* 1982) and 1979 May (White and Holt 1982). The nonburst spectrum is well described by a power law with energy index $\alpha = 0.9^{+0.2}_{-0.1}$ and a low energy absorption equivalent to a hydrogen column density of $N_{\rm H} = 4.0^{+2.3}_{-3.4} \times 10^{21}$ cm^{-3} or a thermal bremsstrahlung model with $kT = 9.3^{+1.8}_{-1.3}$ keV and $N_{\rm H} < 2.5 \times 10^{21}$ cm^{-3}. This spectrum agrees with those measured with the MPC in 1980 June (McClintock *et al.* 1982) and 1979 May (White and Holt 1982).

The burst is apparent in the MPC PHA and TIP count rates shown in Figure 1. Using the PHA data alone, we are

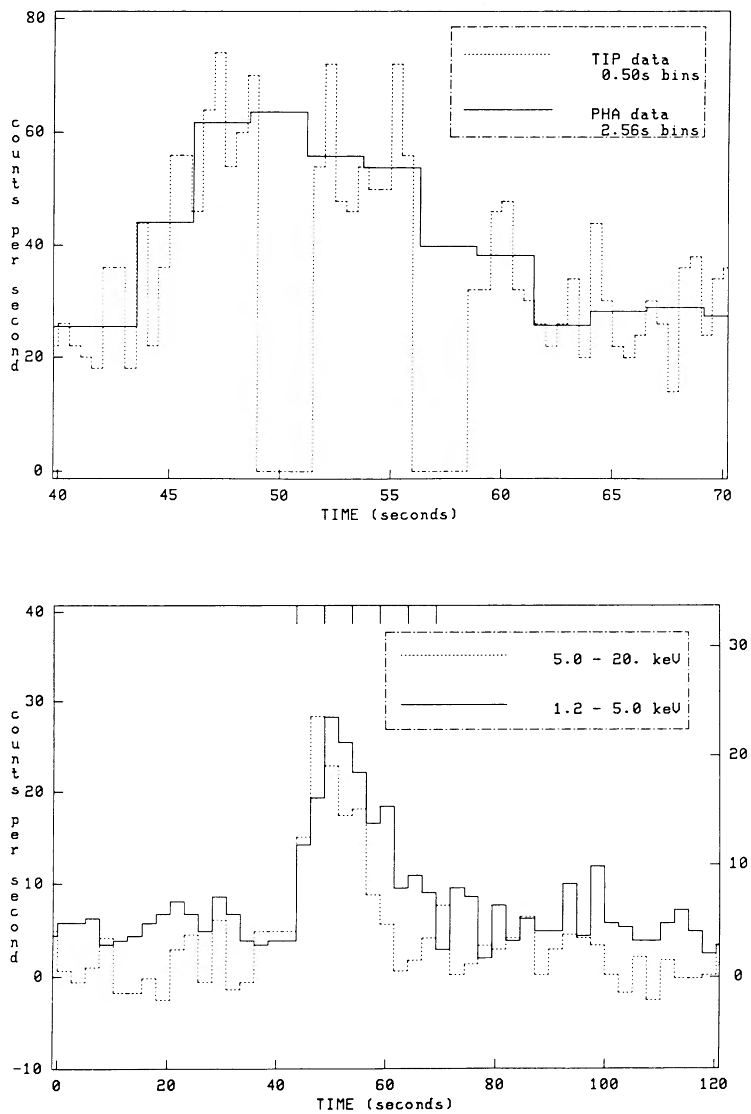

FIG. 1.—(*a*) MPC PHA (*solid curve*) and TIP (*dashed curve*) count rates in the 1.2–20 keV band, including a background of 17.2 ± 0.3 counts s^{-1}. The PHA data are in 2.56 s bins, and the TIP data have been binned into count rates every 0.5 s. Gaps in the TIP data caused by telemetry limitations are shown with zero count rate. The burst rise time of 6.5 ± 1.5 s is evident. The errors appropriate for these data are those due to Poisson statistics in the 2.56 s and 0.5 s bins. (*b*) MPC PHA counting rates in the 1.2–5.0 keV and 5.0–20.0 keV bands. Background rates of 4.57 ± 0.07 counts s^{-1} and 12.7 ± 0.3 counts s^{-1} have been subtracted from the soft and hard bands, respectively. The five 5.12 s long segments which have been fit to blackbody spectra are indicated at the top. The axis on the left refers to the 5.0–20 keV data; the one on the right, to the 1.2–5.0 keV data.

TABLE 1

SPECTRAL PROPERTIES OF BURST FROM 4U 2129+47

Segment[a]	kT (keV)	Flux (1.2–20 keV) ($\times 10^{-9}$ ergs cm $^{-2}$ s^{-1})	χ^2/ν
1..........	$2.8^{+0.9}_{-0.7}$	0.94	2.4/6
2..........	$1.7^{+0.1}_{-0.3}$	0.75	7.0/6
3..........	$1.9^{+0.4}_{-0.4}$	0.49	2.8/6
4..........	$1.1^{+0.3}_{-0.3}$	0.17	7.9/5
5..........	$0.8^{+0.4}_{-0.2}$	0.10	4.8/5

[a]Segments of the data are in units of 5.12 s and are marked on Fig. 1*b*.

able to restrict the rise time of the burst (in the 1.2–20 keV and 1.2–5.0 keV bands) to be between 5.12 and 7.68 s. By using the TIP data, which we have binned into 0.5 s segments (Fig. 1*a*), we are able to estimate the 1.2–20 keV rise time as 6.5 ± 1.5 s. Figure 1*b* shows the increasing dominance of photons in the lower energy band later in the burst, indicating the spectrum becomes softer during the decay.

We have subtracted the average preburst and postburst source count rates in each energy channel from those obtained during the burst and fitted the remaining counts to single blackbody models. The color temperature (T_c), bolometric flux, and χ^2 determined by fits to the counts collected in 5.12 s intervals are shown in Table 1. As we will compare this color temperature to the values of T_c found by previous researchers, the effects of Compton scattering and general relativity on the spectral shape are not appropriate to include here. Corrections to the total computed luminosity due to these effects have also been neglected as they are small in the context of the discussion which follows (cf. Ebisuzaki, Hanawa, and Sugimoto 1984). The color temperature as a function of time is shown in Figure 2. The fall of the temperature during the decay, typical of type 1 X-ray bursts (Hoffman, Marshall, and Lewin 1978), can be clearly seen. The peak flux reached is $\sim 10^{-9}$ ergs cm^{-2} s^{-1} (2–10 keV), and the peak color temperature is $2.8^{+0.9}_{-0.7}$ keV.

During this MPC observation the High Resolution Imager (HRI) (Giacconi *et al.* 1979) was at the focus of the *Einstein* telescope. There are four sources detected at $\gtrsim 5\ \sigma$ in the HRI image, one of which is 4U 2129+47. The observed count rates of these sources may be used to pinpoint the source of the burst more accurately than is possible with the MPC. The average count rate from 4U 2129+47 (in a detection cell of 18″ radius) is 0.20 ± 0.01 counts s^{-1}. The other three sources are very weak, having a total of 9, 8 and 5 counts detected in the ~ 2000 s observation. The source of the burst cannot be any one of these three sources, as the HRI detects no counts from any of them during the burst. If the HRI count rate remained unchanged during the burst, we would expect to observe 5 counts from 4U 2129+47 in the ~ 25 s during which the burst occurs. The probability that the 11 counts actually observed are caused by a Poisson fluctuation is 1.4%. The HRI counts therefore allow us to confirm the presence of an increase in the count rate with 98.4% confidence. Extrapolating the burst and steady state spectrum of 4U 2129+47 as measured by the MPC into the energy range of the HRI (0.1–4.0 keV) we predict $9.7^{+2.2}_{-3.2}$ counts during the X-ray burst, so the increase detected with the HRI is consistent with the burst detected with the MPC. (This uncertainty includes the errors in the MPC spectral fits.)

III. DISCUSSION

The basic mechanism of type 1 X-ray bursts is understood as due to thermonuclear flashes on the surface of a neutron star (Joss 1978; Ayasli and Joss 1982; Taam 1982). While there are many remaining gaps in our understanding of the details of individual bursts (Matsuoka 1985), and there is clearly a range in the characteristics of bursts, their average properties are nevertheless similar enough that they may be used as probes in the investigation of other phenomena.

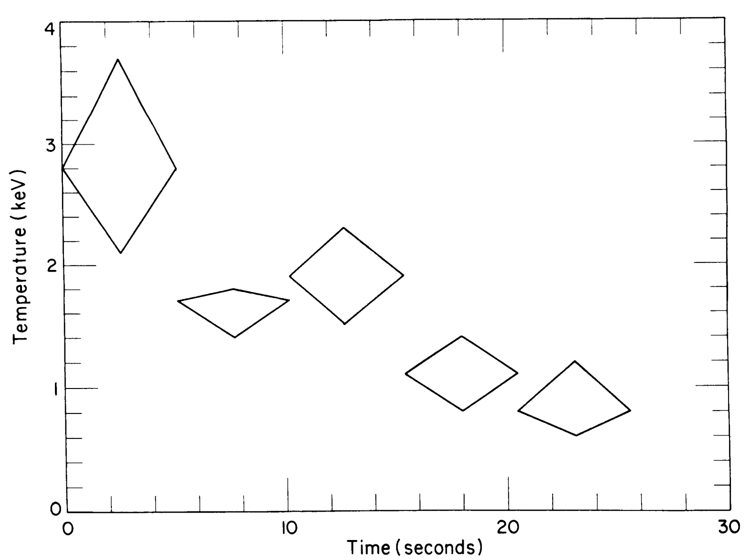

FIG. 2.—Best-fit blackbody color temperature and its 1 σ error during the burst. The data have been fitted in 5.12 s intervals, giving five segments during the burst. The spectral softening typical of type 1 bursts can be seen in the steady decrease of the best-fit temperature. The peak temperature is $2.8^{+0.9}_{-0.7}$ keV.

Most notably, the cooling blackbody spectra of bursts have been used to estimate the radii of many neutron stars, consistently yielding ~ 10 km, and (in one case) the observation of an absorption line may allow measurement of the gravitational redshift on the surface of a neutron star (Waki *et al.* 1984). The hypothesis (justified at least in the case of 4U 1820−30; Vacca, Lewin, and van Paradijs 1986) that the peak luminosity of most bursts is near the Eddington limit has been used to measure the distance to the Galactic center as ~ 7 kpc (Ebisuzaki, Hanawa, and Sugimoto 1984; see also van Paradijs 1978). We note that this distance is correct if there are no selection effects in the observed burst sources (Vacca, Lewin, and van Paradijs 1986).

The observations of this burst may be used in two different ways: if one assumes a set of intrinsic (before scattering) burst parameters, the conditions in the scattering ADC can be derived, or alternatively, if one assumes a set of ADC parameters, the intrinsic burst parameters may be derived. We feel that the properties of bursts are better known than those of ADCs, and so we prefer to adopt the former methodology. There are about 30 burst sources known, from which hundreds of bursts have been studied, and only a few sources (e.g., White and Holt 1982) in which the ADC is clearly the dominant source of X-ray flux and therefore can be well studied. Bursts are clearly not all identical, but the *average* properties of bursts are well defined in three respects: their peak luminosities, rise times, and peak temperatures (Lewin and Joss 1983 and references therein). Ebisuzaki, Hanawa, and Sugimoto (1984) summarize recent observational and theoretical evidence that the strongest bursts reach peak fluxes corresponding to a luminosity near the Eddington limit. Van Paradijs (1978) has studied the peak flux reached by 10 bursters and found that the dispersion of this quantity (for each individual burster) is $\lesssim 40\%$. Lewin *et al.* (1980) studied 53 bursts from 4U 1735−44 and found the dispersion in the peak flux was 37%. The weakest and strongest burst differed in peak flux by a factor of 7. Similar results have been reported for other sources (Lewin and Joss 1983 and references therein). The typical rise time of X-ray bursts seen in 4U 1728−34 (Basinska *et al.* 1984), NGC 6624 (Grindlay *et al.* 1976; Clark *et al.* 1976), and 4U 1636−53 (Inoue *et al.* 1984) is $\lesssim 2$ s. The rise times of bursts from five other sources shown by Lewin and Joss (1983) are similarly $\lesssim 2$ s. The longest rise time reported in the above data set is in excess of 5 s and occurred in one out of 42 bursts seen from 4U 1728−34 (Basinska *et al.* 1984). These rise times have been measured over a variety of energy bandwidths, ranging from 2–6 keV to 1–20 keV. The apparent peak color temperature reached in bursts, as determined by fits to blackbody spectral shapes (uncorrected for the effects of general relativity or Compton scattering), ranges from 2 to 3 keV.

The burst we have discovered from 4U 2129+47 differs from these typical properties most notably in that the peak flux corresponds to an apparent luminosity of (for distances from 1.2 kpc [Thorstensen *et al.* 1979] to 2.2 kpc [McClintock, Remillard, and Margon 1981]) 1.6×10^{35} ergs s^{-1} to 5.5×10^{35} ergs s^{-1}, which is a factor of ~ 500 times less than that typically seen in X-ray bursts. Because of this low peak apparent luminosity, the equivalent blackbody radius for the emitting region is ~ 0.5 km, substantially smaller than the 10 km radius usually found. In addition, the apparent rise time may be longer (~ 6.5 s in the 1–20 keV band, as opposed to $\lesssim 2$ s usually found) and the apparent peak temperature may be higher (~ 3 keV as opposed to 2 keV) than previously measured average values, although both of these may be consistent with extreme values previously observed for bursts. These differences can be understood in terms of the ADC model of 4U 2129+47 and may be used to probe the structure of the corona.

Our observations support the ADC model (McClintock *et al.* 1982) and, in fact, the observed unusual properties of the burst are expected with this model. Therefore, in what follows, we assume the basic ADC model is correct (though its parameters may be uncertain) and that the intrinsic properties of the burst from 4U 2129+47 are typical: the peak luminosity is nearly Eddington, the peak temperature is ~ 2 keV, and the rise time is $\lesssim 2$ s.

The low apparent luminosity indicates that the central source is blocked from our direct view by the accretion disk. The fraction of the intrinsic luminosity which we detect must be scattered off the accretion disk corona. A study of the system's geometry and X-ray–to–optical flux ratio by McClintock *et al.* (1982) indicates that this fraction is $\sim 1\%$–10%. Analysis of the structure of ADCs (Begelman and McKee 1984) indicates a similar value for this fraction. Our observations provide a third independent measurement of this fraction and are consistent with the two previous measurements if the peak luminosity of this burst was ~ 10 times below the Eddington limit. Given the range of peak burst luminosities previously observed, this is plausible.

We interpret the longer than typical rise time as due to the light travel time differences introduced by the scattering of the X-rays off a large ADC. The fact that the rise time at higher energies can be longer than that at lower energies (Clark *et al.* 1976) raises the possibility that the long rise time we measure is an artifact of the relatively wide energy band we have chosen. However, we feel that this effect cannot explain the long rise because (1) many of the previously measured rise times cover similarly wide energy bands and (2) the rise time observed in the soft (1.2–5.0 keV) band of between 5.12 and 7.68 s is also longer than average. An estimate of the electron scattering optical depth derived from the observed 6.5 s rise time is $\tau_{es} \lesssim (2 \times 10^{11}/R)$ cm, where R is the radius of the ADC. This upper limit is derived (under the assumption of spherical symmetry) by accounting for the random walk nature of electron scattering but neglecting any effects due to a nonzero initial rise time and differences in light travel time to the observer from different locations on the surface of the ADC. The duration of the eclipse and orbital separation of the system components indicates $R \approx 4 \times 10^{10}$ cm (McClintock *et al.* 1982) and therefore $\tau_{es} \lesssim 5$.

If the temperature of the ADC is substantially higher (or lower) than the few keV temperature typical of X-ray bursts we would expect to see the effects of inverse Compton (or Compton) scattering in the burst spectrum. While the observed range of peak T_c's is 2–3 keV, bursts with $T_c \approx 3$ keV appear to violate the Eddington luminosity limit and often show evidence of radius expansion (Inoue *et al.* 1984; Basinska *et al.* 1984) in the form of double-peaked profiles. The peak T_c measured in nine out of 12 bursts from MXB 1636−536 which are sub-Eddington is ~ 2 keV, and for the remaining three which show evidence of radius expansion (and therefore apparently reach or exceed the Eddington luminosity) is ~ 3 keV (Inoue *et al.* 1984). Since there is no evidence for radius expansion or a double-peaked profile in this burst from 4U 2129+47, we expect the intrinsic peak color temperature to be ~ 2 keV. The apparent color temperature of $2.8^{+0.9}_{-0.7}$ keV is therefore marginal evidence for Comptonization. The temperature of the ADC ($T_{\rm ADC}$) in 4U 2129+47 as determined by a fit to a single thermal bremsstrahlung spectrum is ~ 8 keV (White and Holt 1982). The possible increase in the observed burst temperature from 2 to 3 keV therefore indicates $\tau_{\rm es} \approx 2.5$ (Rybicki and Lightman 1979). Begelman and McKee (1983) fit a partially Comptonized thermal spectrum to the same (White and Holt 1982) data and find a temperature of ~ 2.1 keV. If this is the true electron temperature, the observed increase in photon energy implies $\tau_{\rm es} \approx 5$. However, we note that $\tau_{\rm es}$ cannot be substantially higher than this because the observed color temperature falls during the burst decay. At much higher optical depths the photons from the burst would be thermalized at the temperature of the corona and would produce a constant temperature for the burst, contrary to observation.

Since this burst appears to be unique among those reported (from neutron stars), can we properly rule out the occurrence of a similarly unique event on a white dwarf? Simple energetic arguments cannot rule this out hypothesis. The gravitational potential energy released by $\sim 10^{20}$ g falling onto a white dwarf could produce the observed flux. However, the energy must be thermalized over a small area (~ 0.5 km) of the white dwarf surface to produce the observed temperatures. This seems implausible as the smallest observed X-ray emitting areas of white dwarfs are the polar caps of the magnetic CVs, and these are typically ~ 100 km in size (Liebert and Stockman 1985). Since the observed properties of the burst are entirely consistent with the ADC model of the source provided the compact object is a neutron star, we feel that this interpretation is more straightforward than requiring a totally new phenomenon in a CV.

Previous measurements of the dynamical masses of the stars in the 4U 2129+47 system indicate a neutron star mass smaller than any other previously measured. These measurements have been done while the X-ray source was in a "high state" and therefore could be in error due to the complex and variable behavior of emission and absorption lines (on which they are based) in interacting binaries. Indeed, the measurement of the mass as $0.53^{+1.0}_{-0.4}$ $M_\odot$ by Thorstensen and Charles (1982), which used velocities determined from the He II 4686 emission line, may be in error due to recently discovered line profile variations (Horne, Verbunt, and Schneider 1986). The mass determination by Horne, Verbunt, and Schneider (1986) is more robust since it is based on the velocity of the narrow core of the Hβ absorption line as well as the He II emission line. However, the absorption line profiles can also be filled in and distorted by emission lines due to the accretion disk or stream (e.g., Mazeh *et al.* 1986), therefore leading to erroneous K velocities, although this effect most naturally leads to erroneously *high* (not low) determinations of the K velocity and system mass.

The X-ray flux from 4U 2129+47 has recently been reported to have turned off, and with it the optical modulation caused by X-ray heating has disappeared (Pietsch *et al.* 1986). The emission lines caused by the accretion disk and reprocessing of X-ray flux may be largely absent at the present time. We therefore have an opportunity to measure the radial velocity variations of the presumed dwarf companion without the interference of the emission lines, allowing an accurate determination of the mass of the neutron star in this source. A program of velocity measurements of the system has therefore been initiated with the MMT and will be reported elsewhere.

IV. SUMMARY

We have detected a type 1 X-ray burst from 4U 2129+47. This allows us to unambiguously identify the compact component of 4U 2129+47 as a neutron star. The apparently atypical properties of this burst can be self-consistently explained as due to the ADC. If one assumes that the intrinsic burst properties are typical, the observations allow probing of the ADC structure and indicate $\tau_{\rm es} \lesssim 2 \times 10^{11}/R$ cm, and $\tau_{\rm es} \approx 2.5$ if $T_{\rm ADC} \approx 8$ keV. Future observations of bursts from this source may be used to set more rigorous constraints on the ADC structure. If the 0.6 ± 0.2 $M_\odot$ mass determination of Horne, Verbunt, and Schneider (1986) is borne out, this will be the first neutron star with a mass significantly less than the Chandrasekhar limit. The method by which such a low-mass neutron star could form in a binary system is unclear.

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