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A GBT Search for Water Masers in Nearby AGNs

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ABSTRACT

Using the Green Bank Telescope, we have conducted a survey for 1.3 cm water maser emission toward the nuclei of nearby active galaxies, the most sensitive large survey for H_2O masers to date. Among 145 galaxies observed, maser emission was newly detected in eleven sources and confirmed in one other. Our survey targeted nearby (v < 12,000 km s^{-1}), mainly type 2 AGNs north of $\delta = -20°$, and includes a few additional sources as well. We find that more than a third of Seyfert 2 galaxies have strong maser emission, though the detection rate declines beyond v $\sim$ 5000 km s^{-1} due to sensitivity limits. Two of the masers discovered during this survey are found in unexpected hosts: NGC 4151 (Seyfert 1.5) and NGC 2782 (starburst). We discuss the possible relations between the large X-ray column to NGC 4151 and a possible hidden AGN in NGC 2782 to the detected masers. Four of the masers discovered here, NGC 591, NGC 4388, NGC 5728 and NGC 6323, have high-velocity lines symmetrically spaced about the systemic velocity, a likely signature of molecular gas in a nuclear accretion disk. The maser

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source in NGC 6323, in particular, reveals the classic spectrum of a "disk maser" represented by three distinct groups of Doppler components. Future single-dish and VLBI observations of these four galaxies could provide a measurement of the distance to each galaxy, and of the Hubble constant, independent of standard candle calibrations.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — ISM: molecules — masers — radio lines: galaxies

1. Introduction

Water vapor masers form in warm (300 – 1000 K), dense ($10^7 - 10^{11}$ cm^{-3}) gas and are common in the envelopes of late-type stars and in star-forming regions. They have been detected throughout the Milky Way and in many external galaxies as well. Some extragalactic water masers are simply analogues to the masers seen in star-forming clouds in our own galaxy. Others are found in more exotic locations, especially the accretion disks and gaseous outflows associated with active galactic nuclei (AGN). Owing to their large apparent isotropic luminosity, and following the terminology applied to strong extragalactic OH masers, those H_2O masers detected in active galactic nuclei have been called "megamasers". Review articles on the topic of water megamasers have been written recently by Maloney (2002), Greenhill (2002) and Henkel and Braatz (2003).

At 1.3 cm wavelength, water masers can be imaged with mas resolution using VLBI. Maps of masers in the nearby Sy 2/LINER nucleus of NGC 4258 (Greenhill et al. 1995b; Miyoshi et al. 1995; Herrnstein et al. 1999) showed that they arise in a thin, warped, edge-on disk at a galactocentric radius of 0.14 – 0.28 pc. Maser components near the systemic velocity form in clouds on the near side of the disk, and "satellite lines" with velocities up to $\pm$ 1100 km s^{-1} (Humphreys et al. 2003) from systemic form in gas located at points viewed tangentially to its orbital path. The maser disk in NGC 4258 follows a Keplerian rotation curve and implies a central mass of 3.9 $\times$ 10^7 M$_\odot$ (Herrnstein et al. 1999). The satellite lines also reveal the angular size of the disk as well as its shape (i.e. the warp).

The velocities of maser lines near the systemic velocity in NGC 4258 drift redward through a $\sim$ 100 km s^{-1} window at a rate of about 9 km s^{-1} yr^{-1} (Haschick, Baan & Peng 1994; Greenhill et al. 1995a). The drift reveals the centripetal acceleration of gas in the disk as it moves across our line of sight to the central core. Herrnstein et al. (1999) developed a model of the maser disk based on its VLBI structure, and combined their derived disk parameters with the measured acceleration to calculate the linear size of the disk. Comparing the linear size of the disk with its angular size, they determined a distance to the galaxy independent of the usual use of standard candles. The authors also used the independent technique of proper motions to confirm the result. Establishing a set of distances to other galaxies using these techniques would provide a new foundation to the extragalactic distance ladder uncoupled from other methods that have historically involved large systematic uncertainties.

There has been a resurgent interest in surveys for extragalactic water maser sources in recent years, inspired by both the above issues and new instrumentation. Programs by Hagiwara, Diamond and Miyoshi (2002), Henkel et al. (2002), Greenhill et al (2003), Hagiwara et al. (2003), Kondratko et al. (2003), and Peck et al. (2003), among others, have increased the number of known extragalactic H_2O masers to ~ 50. Still, only a few of these masers have the signature of a nuclear disk, and more examples are needed.

In this paper we discuss the results of a new survey for H_2O maser emission from a sample of nearby (v $< 12{,}000$ km s^{-1}) galaxies, nearly all AGNs. With the goal of maximizing the detection rate and searching for disk maser candidates, we concentrated on type 2 Seyferts and LINERs, which are known to be the most likely hosts of detectable masers (Braatz, Wilson & Henkel 1997). The candidates were primarily selected from the CfA Seyfert Catalog (Huchra, available at http://cfa-www.harvard.edu/∼huchra), a collection of AGNs drawn from CfA redshift surveys and identifications of X-ray and infrared sources. Eight galaxies in our survey are not in this catalog but were of interest because of strong infrared luminosity or known nonstellar nuclear activity. These are IC 694, IC 4553, NGC 3660, NGC 4013, NGC 5635, NGC 5953, NGC 6211, and UGC 3995A.

Each of the galaxies observed during the present survey has been observed in at least one previous survey for water vapor maser emission, e.g. by Braatz, Wilson & Henkel (1996), Greenhill et al. (1997) or Taylor et al. (2002). The motivation to reobserve these sources comes primarily from recent advances in K-band sensitivity, especially due to the availability of the Robert C. Byrd Green Bank Telescope (GBT). In addition, the availability of large bandwidth (> 200 MHz) spectrometer modes now makes it possible to search efficiently for high-velocity lines. Finally, the intrinsic variability of H_2O masers makes it worthwhile to reobserve sources even if they have been previously undetected. Galaxies already known to host H_2O masers were not observed during this survey, but are being studied as part of other programs, e.g. Braatz et al. (2003).

2. Observations

Observations were made with the GBT during several sessions between 2003 March 4 and 2004 February 28. This period marked a steady improvement in the GBT's high frequency observing capabilities, particularly with regard to baseline stability, pointing accuracy, focus tracking, and sensitivity. We used the 18 – 22 GHz K-band receiver, which has two beams at a fixed separation of $3'$ in azimuth. The GBT beam width is $\sim 36''$ at 22 GHz, and pointing uncertainties were $3'' - 8''$. The telescope was nodded between two positions on the sky such that the source was always in one of the two beams during integration. Prior to 2003 June 4, we observed with the electronic beam switch in the receiver cycling at a rate of 1 Hz, and used a nod cycle of 5 minutes. After that date, we observed with no electronic beam switching, and we shortened the nod cycle to 2 minutes. The latter configuration provided equally good baselines, a simpler data format, and better system reliability since a sometimes faulty electronic switch was bypassed.

The spectrometer was configured with two 200 MHz bandpasses, one centered on the systemic velocity of the galaxy and the second redshifted by 180 MHz. Channel spacing in the spectra corresponds to 0.33 km s^{-1}. The zenith system temperature was between 35K and 80K. Atmospheric opacity was either measured with tipping scans or estimated from system temperature and weather data, and ranged from 0.04 to 0.12 at the zenith. Data were reduced using AIPS++. When baseline stability permitted, we smoothed the reference spectra prior to calibration using a 16 channel boxcar function, to improve sensitivity. In most cases we subtracted a polynomial (order between 3 and 6) from the 200 MHz spectrum to remove the baseline shape. For some galaxies we subtracted a baseline structure derived from the lowest frequency Fourier components of the spectrum. The 1σ r.m.s. sensitivity of the survey ranges between 3 and 6 mJy per 24.4 kHz ($\sim$0.33 km s^{-1}) channel. This sensitivity is equivalent to roughly 0.5 $L_\odot$ for a 1 km s^{-1} line in a galaxy with a recession velocity of 5000 km s^{-1}.

Velocities throughout this paper follow the optical definition of Doppler shift and are calculated with respect to the Local Standard of Rest (LSR). Galaxy recession velocities are derived either from 21 cm HI observations or optical observations. Galaxy distances are calculated using $H_0 = 75$ km s^{-1} Mpc^{-1}.

3. Results and Discussion

We observed 145 nearby AGNs during the survey, and detected masers in 12 galaxies (Table 1), giving a detection rate of 8.3%. Without our knowledge at the time of the observation, one of these masers (in Mrk 1066) had been detected at Effelsberg by Peck et al (2003); the other 11 are new discoveries. Maser emission has been detected in each of the 12 galaxies with the GBT on at least two epochs, and the best spectrum for each one is shown in Figure 1. A complete presentation of data and an analysis of the variability in these sources will be presented in a later publication. The total number of galaxies, excluding the Milky Way, with detected H_2O masers is now 63. Table 1 lists the galaxies detected during this survey and Table 2 lists those observed but not detected. Each galaxy was observed toward its nucleus. No maser emission was detected in any of the galaxies in the second bandpass, shifted by 180 MHz. A more comprehensive list of galaxies observed for H_2O maser emission, including this survey and others, is available from http://www.nrao.edu/∼jbraatz, and a list of known extragalactic maser systems is available at the site as well.

The galaxies observed during this survey do not form a complete sample but the results can still be used to improve our knowledge of the incidence of detectable masers in AGNs. Among galaxies listed as Seyfert 2 type in the CfA AGN list (see Sect. 1) and observed with the GBT (either during the present survey or during previous observations of known H_2O masers, e.g. Braatz et al. 2003), the fraction detected is 17/82 = 21%, 14/55 = 25%, and 11/39 = 38% for galaxies within 12,000 km s^{-1}, 7500 km s^{-1}, and 5000 km s^{-1}, respectively. Such a decrease of detection rate with increasing distance reflects the sensitivity limitation of surveys such as this (see Braatz, Wilson & Henkel 1997). In the listed distance categories, there were 15, 9, and 2 galaxies, respectively, from the CfA list not observed during this survey. The LINER sample is less complete than the Seyfert 2 sample, so likewise statistics are less instructive for this class of AGN. Still we note that the detection rate is 5/42 = 12%, 5/40 = 13%, and 4/36 = 11% for LINERs from the present survey in the same three distance categories.

Two of the sources detected in this survey, NGC 2782 and NGC 4151, are included in Carl Seyfert's original list of twelve "Emission Line Galaxies" (Seyfert, 1943) that defined the Seyfert type, and it is interesting to note that five of those twelve have now been detected in H_2O maser emission. However, NGC 2782 and NGC 4151 are not usually classified as type 2 AGNs, counter to the trend of most other extragalactic H_2O masers. NGC 2782 has a powerful nuclear starburst but the high luminosity of the water masers ($L_{iso} = 12L_{\odot}$) suggests the presence of an AGN. Kennicutt, Keel & Blaha (1989) find that the profiles of the Hβ and [OIII]$\lambda\lambda$ 4959, 5007 lines are dramatically different, with [OIII] showing both a broader core and high velocity wings. They conclude that the high velocity gas in the wings of [OIII] must have very high excitation, reminiscent of the narrow line emission in Seyfert galaxies, and that the nucleus may be a "composite" (i.e. starburst plus AGN) system (cf. Véron, Gonçalves & Véron-Cetty 1997). Other workers (e.g. Schulz et al. 1998) have, however, interpreted the high excitation gas in terms of a starburst-driven superwind, so the evidence for an AGN in NGC 2782 is not compelling. A hard X-ray spectrum of this galaxy could settle the issue.

NGC 4151 is a nearby (13.3 Mpc) active galaxy usually classified as a Seyfert 1.5 (e.g., Osterbrock & Koski 1976), but the broad emission lines in its optical spectrum are variable (e.g. Sergeev, Pronik & Sergeeva 2001) giving it a Seyfert 2 profile at times. The galaxy has a large X-ray column density toward its nucleus ($\sim 10^{23}$ cm^{-2}, Weaver et al. 1994). The proximity of NGC 4151 and this large X-ray column are conducive to the detection of water vapor emission. Braatz et al. (1997) concluded that the probability of H_2O maser emission in Seyfert galaxies increases with increasing X-ray inferred column density to the nucleus. The X-ray measured column density to the nucleus of NGC 4151 is roughly two orders of magnitude larger than that toward a typical Seyfert 1, and is similar to the column found among typical Seyfert 2s (Turner et al. 1997). At 0.7 $L_{\odot}$, the isotropic luminosity of the maser in NGC 4151 is among the weakest of any detected in an AGN. The maser emission is primarily confined to two narrow components (see Figure 1), one at 692.4 km s^{-1} and the other at 1126.6 km s^{-1}. The widths of the emission lines, determined from Gaussian fits, are 1.2 and 1.5 km s^{-1} (full width at half maximum), respectively. NGC 4151 has been searched previously for H_2O emission, but not detected. The most sensitive previous observation, obtained on 2000 March 20, resulted in a 3σ detection limit of 9 mJy per 4.2 km s^{-1} channel (Taylor et al. 2002). Our detection shows the lines having peak flux densities of 36 and 53 mJy (Figure 1), but the lines are narrower than the channel spacing used by Taylor et al. The peak flux densities in our spectrum are reduced to $\sim$11 and $\sim$19 mJy after averaging to a channel spacing of 4.2 km s^{-1}. That these fluxes are still above the Taylor et al. detection limit may reflect intrinsic variability in the NGC 4151 maser.

Three sources detected in this survey are associated with merging systems: NGC 2782, NGC 4922, and NGC 5256. In NGC 4922 the separation of the merging nuclei is 22$''$ (10 kpc) and each nucleus is itself an AGN. NGC 5256 is similar, with two AGNs in the merger separated by 11$''$ (5.9 kpc). In both systems, an observation was made toward each of the nuclei to determine the source of the H_2O emission. In NGC 4922 the observations are consistent with all of the detected maser emission originating from component NGC 4922N (the more northern component) and in NGC 5256 the observations are consistent with all of the detected maser emission originating in NGC 5256S (the more southern component).

The masers detected in NGC 591, NGC 4388, NGC 5728 and NGC 6323 all reveal high-velocity features approximately symmetrically spaced about the systemic velocity of the galaxy, a possible signature of a nuclear disk. In this interpretation, the maximum rotation velocities would be $\sim$425, $\sim$400, $\sim$250 and $\sim$550 km s^{-1} respectively. Two of these galaxies, NGC 4388 and NGC 5728, are known to have a well defined, bi-conically shaped narrow line region (Pogge 1988; Corbin, Baldwin & Wilson 1988; Wilson et al. 1993), a characteristic feature of a highly inclined, optically thick nuclear torus around the source of ionizing radiation. NGC 6323 has the classic maser spectrum expected from a nuclear disk, with a distinct cluster of Doppler components near its systemic velocity in addition to the high-velocity lines. At a distance of ∼100 Mpc, 14 times more distant than NGC 4258, NGC 6323 is a strong candidate for detailed VLBI studies that could ultimately provide a direct measurement of the Hubble constant. Because of the faintness of its masers, a global array of telescopes including the GBT, Effelsberg, and Goldstone in addition to the VLBA would be essential to map the disk.

4. Summary

We searched 145 nearby active galaxies for 1.3 cm H_2O maser emission and detected 12 galaxies. Although each of these galaxies has been observed but not detected in H_2O during previous surveys, we attained a fairly high detection rate of 8.3% due to the improved sensitivity of this survey. Four of the newly discovered masers have spectral profiles consistent with a disk maser and might become useful subjects of followup observations to map the disk, characterize the kinematics, and perhaps make direct measurements of the distances to the host galaxies. Our results indicate that greater than a third of Seyfert 2 galaxies host water megamasers, though the detection rate declines for galaxies beyond ~ 5000 km s^{-1} due to sensitivity limits. Although Seyfert 2 galaxies are the most likely class of maser host, one of the masers discovered in this survey is in the type 1.5 Seyfert NGC 4151, and another is in the starburst galaxy NGC 2782. We discuss possible reasons for luminous water maser emission in these two galaxies. Our survey demonstrates that the recent improvements in sensitivity and bandwidth warrant more extensive surveys, including type 1 AGNs, starburst galaxies, and apparently normal galaxies.

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Table 1: H_2O Masers Detected During the GBT Survey

Source	α_{2000}	δ_{2000}	V_{LSR} [a]	S_{peak} [b]	L_{iso} [c]	Date of Observation
	(h m s)	(° ′ ″)	(km s^{-1})	(mJy)	($L_\odot$)	
NGC 591	01 33 31.2	+35 40 06	4554 ± 9	10	25	31 Jan 2004
Mrk 1066	02 59 58.6	+36 49 14	3601 ± 22	48	30	28 Jan 2004
UGC 3255	05 09 50.2	+07 29 00	5674 ± 59	15	16	6 Mar 2003
Mrk 3	06 15 36.3	+71 02 15	4009 ± 6	17	11	28 Jan 2004
Mrk 78	07 42 41.7	+65 10 37	11196 ± 29	28	34	15 Nov 2003
NGC 2782	09 14 05.1	+40 06 49	2560 ± 5	45	12	14 Jan 2004
NGC 4151	12 10 32.6	+39 24 21	1002 ± 3	52	0.7	28 Feb 2004
NGC 4388	12 25 46.7	+12 39 44	2521 ± 4	15	12	14 Jan 2004
NGC 4922	13 01 25.2	+29 18 50	7080 ± 9	36	190	31 Oct 2003
NGC 5256	13 38 17.2	+48 16 32	8365 ± 13	99	30	4 Nov 2003
NGC 5728	14 42 23.9	−17 15 11	2796 ± 8	173	88	14 Jan 2004
NGC 6323	17 13 18.0	+43 46 56	7791 ± 35	41	480	2 Jun 2003

[a]Recession velocity measured with respect to the local standard of rest. Velocities and uncertainties are from de Vaucouleurs et al. (1991), using HI velocities when available and optical velocities otherwise. For NGC 6323 the optically measured velocity is from Marzke, Huchra & Geller (1996).

[b]Peak flux density

[c]Inferred isotropic luminosity of the maser emission.

Table 2: Galaxies Undetected in H_2O Emission

0152+0622	IC 4553	NGC 334	NGC 3660	NGC 5427
0253-1641	II Zw 101	NGC 404	NGC 3898	NGC 5635
0258-1136	Mrk 176	NGC 600	NGC 3921	NGC 5674
0335+09	Mrk 198	NGC 788	NGC 3982	NGC 5675
0354-1855	Mrk 273	NGC 1144	NGC 3998	NGC 5695
0414+00	Mrk 298	NGC 1167	NGC 4013	NGC 5851
0445-1741	Mrk 334	NGC 1229	NGC 4036	NGC 5899
0446-2349	Mrk 359	NGC 1358	NGC 4074	NGC 5929
07570+2334	Mrk 372	NGC 1365	NGC 4111	NGC 5953
0816+211	Mrk 403	NGC 1409	NGC 4117	NGC 6211
0942+09	Mrk 423	NGC 1410	NGC 4192	NGC 6251
1034+060	Mrk 461	NGC 1667	NGC 4278	NGC 6500
1116-2909	Mrk 477	NGC 1685	NGC 4303	NGC 6764
1258-3208	Mrk 516	NGC 2110	NGC 4419	NGC 6951
1319-162	Mrk 573	NGC 2273	NGC 4450	NGC 7212
1322+2918	Mrk 612	NGC 2377	NGC 4486	NGC 7217
1335+39	Mrk 622	NGC 2768	NGC 4501	NGC 7450
1431-3237	Mrk 745	NGC 2841	NGC 4569	NGC 7674
1533+14	Mrk 883	NGC 2911	NGC 4579	NGC 7682
1548-0344	Mrk 917	NGC 2992	NGC 4941	NGC 7743
2319+09	Mrk 937	NGC 3010b	NGC 5005	[SP] 55
3C 317	Mrk 955	NGC 3031	NGC 5128	UGC 3995A
Ark 539	Mrk 1058	NGC 3185	NGC 5135	UGC 6100
Fair 1140	Mrk 1073	NGC 3227	NGC 5195	UGC 10567
Fair 1149	Mrk 1098	NGC 3362	NGC 5252	UGC 12056
IC 614	Mrk 1239	NGC 3561	NGC 5283	
IC 694	Mrk 1388	NGC 3642	NGC 5371	

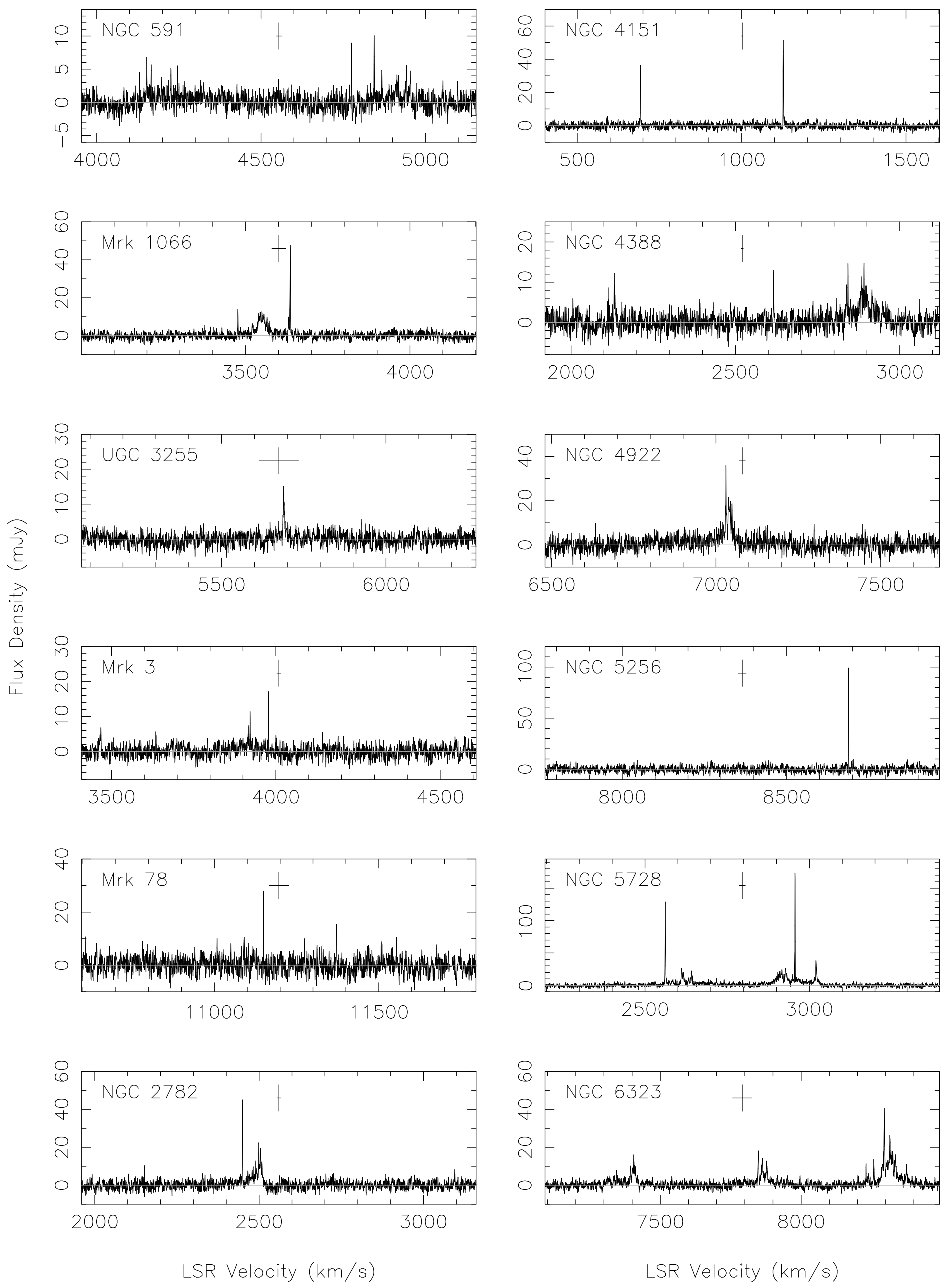

Fig. 1.— Spectra of 1.3 cm water maser emission toward the nuclei of 12 galaxies. Each spectrum covers 1200 km s^{-1} except the one toward NGC 6323, which covers 1400 km s^{-1}. The systemic velocity of each galaxy and its uncertainty are marked above each spectrum by a cross. Velocities are measured with respect to the LSR and use the optical definition of Doppler shift.

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