A METAL ENRICHED DARK CLUSTER OF GALAXIES AT $Z = 1$

Dark lens searches

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1. Introduction

Looking for and studying very distant galaxy clusters, clusters at $z > 1$, are one of the prime subjects of the modern observational cosmology. If the metallicity of the hot intra-cluster medium in very distant galaxy clusters is measured for example, it provides fruitful informations for us to understand the formation and evolution of galaxies. However, difficulty of the study is that there is few confirmed very distant galaxy clusters yet. We first have to search for very distant clusters but it requires very deep observations. A random selection of sky is not practical. We have to select the sky. In this article, it is demonstrated that missing lens problem has close connection with very distant cluster of galaxies and dark lens searches could open a new window for studying very distant cluster of galaxies.

2. Missing lens problem

The word 'missing lens problem' can be found in the unique text book on the gravitational lensing written by Schneider, Ehlers, Falco (1992). It is the problem that there are multiple QSOs which are suspected to be gravitational lens systems, but for which no deflector is observed near the images or only a part of deflector is observed. The difference of the latter cases from the usual missing mass problem is that it requires unusually high mass-to-light ratio compared with that of already known objects. An yet unidentified part of the lens objects as already known objects, such as galaxy and/or galaxy clusters, is called 'dark lens'. The dark lens search is the trial to identify the dark lens objects as already known objects (e.g. Wiklind & Combes 1996). If all the trials in multi wave length with enough deepness failed to find any evidence of already known objects as the lens,

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it could lead us to conclude the existence of an yet unknown new type of object which contains few luminous matter.

A Table 2 summarizes the candidates of the multiply and ring imaged quasar and radio lenses. We can see that a rather large fraction of the lens candidates are showing the missing lens problem.

3. X-ray search for dark lens objects

A dark lens object could be a bright X-ray source since it may accumulate the inter-galactic medium by its strong gravitational field and heat the accumulated gas up to a temperature of a few keV due to the gravitational energy release, especially for the cases of the image separation of a few arcsec or more. Therefore, a deep pointed X-ray observations could be a promising method for identifying the lens objects complemental to optical and infrared searches. Even if the deep X-ray observations failed to find the lens objects, it provides strict upper limit on the fraction of the hot X-ray emitting gas mass in the dark lens objects which is one of the dominant components of luminous matter in the nearby known objects. Non detection in X-ray, therefore, let us cast toward an exciting possibility, that is existence of a dark matter condensation containing few luminous matter.

Motivated by those, we have been performing X-ray search for dark lens objects by using the X-ray satellite ASCA and ROSAT. In the following sections, our results obtained for two objects are summarized.

4. MG2016+112:A dark cluster

MG2016+112 was first discovered as triple radio sources by Lawrence et al. (1984). A part of lenses have been identified as two galaxies, galaxy D at $z = 1.01$ (Schneider et al. 1985 & 1986) and galaxy C (Lawrence et al. 1984). However, only the luminous matter of these galaxies is not enough to explain the observed nature of the lensed images. Narasimha, Subramanian & Chitre (1987) proposed a gravitational lensing model that the quasar MG2016+112 is being lensed by the two galaxies assisted by a cluster of galaxies centered on the galaxy D. However, it was reported that no evidence of the existence of the postulated cluster have been found in spite of deep optical (Schneider et al. 1985) and infrared (Langston et al. 1991) search. We have performed deep X-ray observations of MG2016+112 and found evidences of a cluster of galaxies at $z = 1$ (Hattori et al. 1997).

4.1. THE ASCA OBSERVATIONS

A deep observation of MG2016+112 with the ASCA X-ray observatory was performed from October 24^{th} to 26^{th} 1994, with an effective exposure time of 85 ksec. A new X-ray source (referred to as AXJ2019+1127) was discovered in the direction of the lens system with more than 10σ significance level. Figure 1 shows the X-ray spectrum of AXJ2019+1127 obtained by ASCA. An emission line feature is clearly seen at 3.5 keV which matches with the redshifted Fe K line from a cluster of galaxies at $z = 1$. Assuming that the source is a cluster, the spectrum can be fit with a Raymond-Smith plasma model (Raymond & Smith 1977). The best fitting results are summarized in Table 1. The inclusion of a non-zero abundance reduces χ^2 by 10.01 and is significant at the 99.9% level (3σ). The best fit value of $N_{\rm H}$ is consistent with the Galactic value of $N_{\rm H} = 0.15 \times 10^{22}\rm cm^{-2}$ (Dickey & Lockman 1990). As shown in Fig.3, the observed X-ray luminosity and temperature of AXJ2019+1127 is consistent with the correlation of X-ray gas temperature and X-ray luminosity for distant clusters (Mushotzky & Scharf 1997). These results are consistent with the idea that there is a cluster of galaxies including the galaxy D as a member galaxy.

TABLE 1. The fitting results for the ASCA spectrum of AXJ2019+1127 by Raymond & Smith model. Errors are the 1σ confidence level statistical errors for one interesting parameter except the errors for the redshift where the $\pm 1\%$ systematic error in the ASCA energy scale calibration is included in the 90% statistical errors. The solar iron abundance of 4.67×10^{-5} is adopted (Anders & Grevesse 1989) and throughout the paper except in Fig.3 $H_0 = 50h_{50}$km/s/Mpc and $q_0 = 0.5$ are assumed.

kT keV	Z $\rm Z_\odot$	$L_x(2-10\rm keV)$ $10^{44}h_{50}^{-2}$erg/sec	z	$N_{\rm H}$ $\rm cm^{-2}$	$\chi^2/d.o.f.$
$8.6^{+4.2}_{-3.0}$	$1.7^{+1.25}_{-0.74}$	$8.4^{+2.4}_{-1.7}$	$0.94^{+0.08}_{-0.09}$	$0.18^{+0.15}_{-0.10} \times 10^{22}$	$46.66/52 = 0.90$

4.2. THE ROSAT HRI OBSERVATIONS

Another crucial test for the cluster origin of the X-ray emission would be to resolve the source extent. This was performed with a deep observation with the ROSAT HRI. We find a diffuse source with 76 ± 24 source counts, $(1.4 \pm 0.4) \times 10^{-3}$ cts/sec within a circle of radius $1'$. Fig.2 shows the source image. The peak detection significance of the source is 4.2σ. The maximum of the X-ray emission is consistent with the position of the cD galaxy D within the HRI central position determination accuracy, at most $\sim 20''$, limited both by pointing accuracy and poor photon statistics. The HRI count rate is consistent with, but slightly less than that expected from the ASCA observation, that is $\sim 2.5 \times 10^{-3}$cts/sec. There is no other source above the 3σ significance detection limit in the circle of radius $3'$ centered on MG2016+112 in the HRI field. We therefore conclude that the

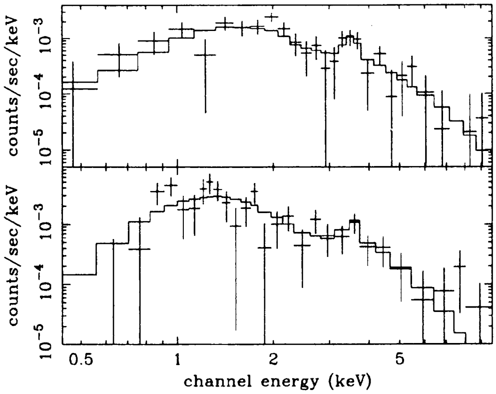

Figure 1. X-ray spectrum of AXJ2019+1127 obtained by ASCA. The background subtracted source spectrum obtained by two GISs (top panel) and by two SISs (bottom panel) with 1σ Poisson errors are shown. The solid lines are the best fit Raymond-Smith models obtained by simultaneous fitting of the GIS and SIS spectra. The background is taken from blank field observations during the test (PV) phase of the ASCA mission. The SIS data were taken with 2CCD bright mode observations with effective exposure time of 22ksec.

source detected by the ROSAT HRI is identical to AXJ2019+1127. Fig.2 shows that the X-ray surface brightness distribution of the source deviates significantly from the profile of the ROSAT HRI point spread function and the source is extended. Since the source counts within a concentric circle monotonically increases up to $1'$, the source radius is estimated to be $1'$ ($500h_{50}^{-1}$kpc for $z = 1$).

4.3. THE MOST DISTANT X-RAY CLUSTER AS A DARK CLUSTER

The above results clearly imply that AXJ2019+1127 is a galaxy cluster in which galaxy D is the central dominant galaxy. This is the most distant galaxy cluster discovered in X-rays so far. Since the X-ray emission provides the best evidence that clusters are gravitationally bound entities (unless a large number of measured galaxy redshifts are available), this is also the most distant clearly confirmed galaxy cluster. The redshift of the next furthest known X-ray cluster is MS1054.5-0321 at $z = 0.826$ (Donahue et al. 1997). Assuming that the cluster is isothermal and in hydrostatic equilibrium, one can obtain a rough estimate of the cluster mass. The best fit results yields a central electron density of $1.7 \times 10^{-2} h_{50}^{0.5}$ cm^{-3}, a gas mass of $2.4 \times 10^{13} h_{50}^{-2.5} \mathrm{M}_{\odot}$ and a gravitational mass of $3.6 \times 10^{14} (kT/8.6\mathrm{keV}) h_{50}^{-1} \mathrm{M}_{\odot}$ within a sphere of radius of $500h_{50}^{-1}$kpc in the cluster. The gas mass fraction of $\sim 7h_{50}^{-1.5}$% of the total mass is typical for the central regions of nearby clusters (Briel et al. 1992) within the measurement errors.

The obtained mass distribution is consistent with the mass model for

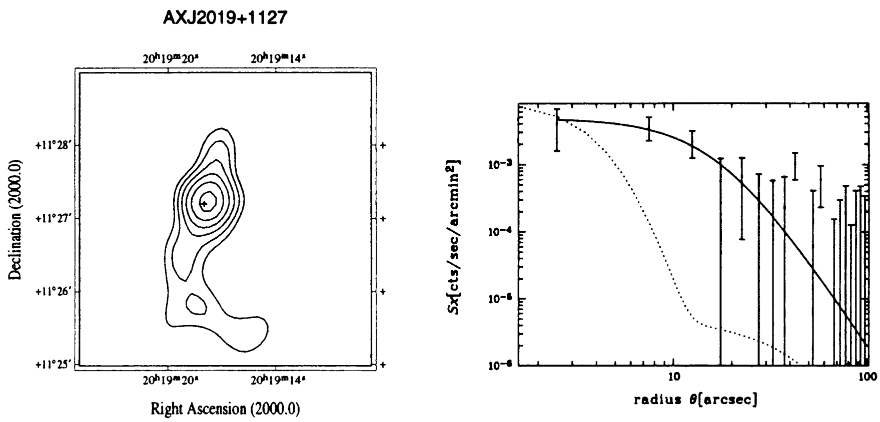

Figure 2. **a.** The left pannel shows that X-ray image of AXJ2019+1127 obtained by the ROSAT HRI. A deep ROSAT HRI observation was performed to resolve the possible extent of the source. The lens system was observed from November 15^{th} to 20^{th} 1995, from April 19^{th} to 28^{th} 1996 and from October 22^{nd} to November 13^{th} 1996 with a total exposure time of 79 ksec, yielding an effective exposure of 53.7 ksec after removal of observing times with high background flux. The accuracy of the HRI pointing is calibrated with two point sources coincident with stars in the Palomar Sky Survey observed in the field. The accuracy of the HRI pointing is better than $9''$. The contours show the significance levels with a linear spacing of 0.5σ from the minimum level of 1.5σ. The peak significance is 4.2σ. The image is smoothed with Gaussian filter with $\sigma = 15''$. The cross shows the position of galaxy D. **b.** The right pannel shows that the background subtracted X-ray surface brightness profile of AXJ2019+1127 obtained by the ROSAT HRI. The ROSAT HRI PSF profile at the same off-axis angle as the source position is also shown (dashed line). The central surface brightness of the PSF is set for a point source at the same central surface brightness as the source. Superposed on the data is the best fit isothermal β model (solid line) with a core radius of $17'' \sim 150h_{50}^{-1}$kpc, and $\beta = 0.9$ (solid line) which is typical for X-ray profiles of nearby rich clusters (Sarazin 1986). The central surface brightness of the model is $\sim 3.3 \times 10^{-3}$cts/sec/arcmin^2.

the lens proposed by NSC (model II in their paper). It implies that we have indeed discovered cluster responsible for the lensing effect additional to galaxy D. Another spectacular result of this discovery is the high iron abundance detected in the intra-cluster medium of AXJ2019+1127. Although the errors on the abundance are quite large, we can safely say that the iron content in this cluster is at least as high as that for nearby clusters of galaxies (Ohashi 1995). Currently the most distant galaxy cluster in which an Fe K-line has been detected is at a redshift of $z = 0.54$ (Donahue 1996). Therefore, AXJ2019+1127 is now the highest redshift cluster for which the existence of a metal enriched intra-cluster medium is confirmed. The detection of the large iron content at high redshift sets a new limit for the epoch of the enrichment. This favors models where early star burst phases in galaxies are responsible for the metal enrichment of the intra-cluster medium (Arnaud et al. 1992; Hattori & Terasawa 1993).

More surprisingly, a high iron abundance has been discovered in this "dark cluster", which is very poor in its galaxy content according to the deep optical and infrared searches (Schneider et al. 1985; Langston et al. 1991). The main optical light source from this cluster is galaxy D which has a blue luminosity of $L_B = 1.1 \times 10^{11} h_{50}^{-2} \mathrm{L}_\odot$. Another possible member galaxy is galaxy C (Lawrence et al. 1984) which, however, can contribute only a fraction of galaxy D in optical luminosity. Therefore, the mass to light ratio of the cluster would be $M/L_B \sim 3300(kT/8.6\mathrm{keV})^{-1} h_{50} M_\odot/L_\odot$! Since according to our current understanding the metal enrichment originates in the stars of the cluster galaxies, it is very puzzling that we detect such a high iron abundance in this "dark cluster". Therefore, either AXJ2019+1127 is a very new and enigmatic object or it has more cluster members at fainter magnitudes that have escaped the deep searches conducted so far. Recently, it has been reported (Ebeling et al. 1995) that there are also some low redshift clusters that are optically dark but bright in X-rays. Combined with our results, this may indicate that there exist many such objects in our universe which have eluded optical identification. In any case, AXJ2019+1127 provides us with a new means for testing cosmological theory and ought to be well studied in various wavelength bands.

4.4. THE MASS DISTRIBUTION OF THE CLUSTERS AT $Z \sim 1$

The radio observation has confirmed that there is no additional images of the lensed quasar MG2016+112 more than $10''$ and less than $2'$ from the brightest image down to two order of magnitude fainter than the brightest image (Schneider et al. 1985). This gives a strong constraint on the mass distribution of AXJ2019+1127 so that the Einstein ring radius of the cluster against the sources at $z = 3.27$ is less than $10''$ or $20''$ if the possibility that the galaxy D is off-center of the cluster within the central determination accuracy, is taken into account. Further observations of AXJ2019+1127 to determine the center of the cluster with very good accuracy may provide an unique opportunity to study the mass distribution of this very high redshift cluster and test the structure formation theory (Navarro, Frenk, White 1995).

5. Q2345+007:A cold cluster

The quasar Q2345+007 has been one of the most mysterious lens candidate double quasar since its discovery (Weedman, et al. 1982). In spite of deep and wide field optical searches for lens object, main lens object has not yet been identified (e.g. Tyson et al. 1986). A very faint galaxy was found edge of the secondary image, B image, after the subtraction of the point spread function of the image (Fischer et al. 1994). Since a C IV doublet absorption line ($z = 1.483$) (Foltz et al. 1984, Steidel & Sargent 1991) was found in the

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B image, the redshift of the faint galaxy is supposed to be 1.483. However, the expected mass of the galaxy is too small to explain the wide separation of the two images unless it has an extremely high mass-to-light ratio. A large cluster at $z = 1.49$ was claimed since both of two images have metal absorption lines with redshift $z = 1.491$. Bonnet et al. (1993) reported the detection of a possible lensing cluster from weak lensing shear field with a strength of $\gamma \sim 0.15$, confirmed by van Waerbeke et al. (1997) and arclet candidates. After this detection, a galaxy cluster candidate was found as an enhancement in the number density of faint galaxies at the right location on the sky predicted by the shear field (Fischer et al. 1994, Mellier et al. 1994). Pello et al. (1996) made photometric redshift estimations for the galaxies in the cluster candidate field and found an excess of galaxies at $z \sim 0.75 \pm 0.1$. Assuming the cluster has this redshift, the velocity dispersion required to produce the observed shear pattern should be 790^{+115}_{-170}km/s (Pello et al. 1996) which corresponds to the hot gas temperature of $kT = 4.1^{+1.3}_{-1.6}$keV. However, the cluster with this velocity dispersion centered at 40″ off from the brightest image can not be the main lens for Q2345+007.

The 46.3ksec exposure of the ROSAT HRI observation and the 80ksec ASCA observations did not detect an X-ray emission from the cluster responsible to the observed shear. It sets 3σ upper limit on the X-ray luminosity of 0.4×10^{44}erg/sec in rest frame 2 – 10keV (Hattori et al. 1997c). In Fig.3, this upper limit and the temperature range expected from the shear field measurement are plotted. Upper limit of the X-ray luminosity is rather small compared with the value expected from its temperature. The cluster may contain little hot gas. However, the errors in the temperature estimation is large because of the simple modeling of the cluster mass distribution, unknown source redshifts and large errors in shear strength measurement and the cluster redshift estimation. Therefore, further observations to constrain the cluster mass from lensing and the spectroscopical measurement of the cluster redshift are very important.

Up to now, dark lens searches for Q2345+007 in multi-wave length have failed in identifying main lens objects as galaxy and/or galaxy cluster. It supports the idea that this double quasar is physically associated and is not lensed single quasar (Kochanek et al. 1997). Kochanek et al. (1997) is arguing that the most of the wide separation angle double quasars without lens could be physical association. However, we have to remind ourself the remarkable similarity of spectra between two images of the double quasars which is of course naturally explained by lensing, compared with the non-similarity of randomly selected two quasars' spectra (Simcoe, Richards, & Turner 1997). If the most of the double quasars are turned out to be physical pair, it requires a new model which controls physical state of two quasars separated by a few$\times$10 – 100kpc (e.g. Arp & Crane 1992).

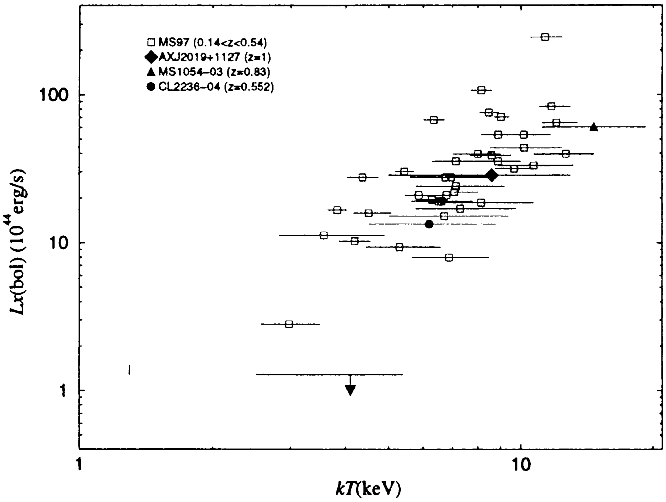

Figure 3. X-ray luminosity vs gas temperature for AXJ2019+1127 and Q2345+007 cluster. In this figure, X-ray luminosity is the bolometric luminosity where $q_0 = 0$ is assumed. The errors in the gas temperature are symmetrized 90% confidence errors. The open squares are clusters at $0.14 < z < 0.54$ from Mushotzky & Scharf (1997), filled diamond is AXJ2019+1127, filled triangle is MS1054-03 at $z = 0.83$ from Donahue et al. (1997), filled circle is CL2236-04 at $z = 0.552$ from Hattori et al. (1997b), and downward pointing arrow is 3σ upper limit of the bolometric luminosity for Q2345+007 cluster where $kT = 4.5$keV is assumed to calculate the bolometric luminosity.

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TABLE 2. Summary of Multiply Imaged Quasars and radio sources. From left to right, the name of source, the source redshift, the separation angle between the two main images, the magnitude of the brightest image, the type of lens where blank means yet no-detection and question mark denotes the cases either the detection of the lens is not secure or unusually high mass-to-light ratio is required, the lens redshift, the number of compact images where an E indicates the images are extended and an R indicates a ring, the degree of security as the gravitational lens where an acc denotes the acceptable case otherwise denoted by question mark, the reference for the first discovery of the source. The listed properties are mainly quoted from Keeton & Kochaneck (1996), Kochaneck, Falco, Muñoz (1997), and http: //www.stsci.edu/ftp/stsci/library/grav_lens/grav_lens.html.

Name	z_s	$\Delta\theta$ ″	m_s mag	Lens	z_l	N_{im}	GL?	Ref
LBQS2153-2056	1.85	7.8				2	?	Hewe97
Q2345 + 007	2.15	7.3	$R = 18.5$	G,CL?	1.5? 0.7?	2	?	Weed82
Q1120 + 0195	1.46	6.5	$R = 15.7$	G?	~ 0.6?	2	?	MD89
QJ0240 − 343	1.41	6.1	$B = 18.6$			2	?	Tin95
Q0957 + 561	1.41	6.1	$R = 16.7$	G,CL	0.36	2	acc	Wals79
LBQS1429-008	2.08	5.1	$R = 17.7$	$R > 24$	1.5?	2	?	Hewe89
MG0023 + 171	0.95	4.8	$r = 22.8$			2	?	Hewi87
Q2138 − 431	1.64	4.5	$B_J = 19.8$	$R > 24$		2	?	Haw97
Q1635 + 267	1.96	3.8	$B = 19.2$	G?	0.6?	2	?	DS84
MG2016 + 112	3.27	3.6	$i = 22.1$	G,CL	1.01	> 3?	acc	Law84
3C194	1.18	3.5	$R = 21.5$	G	0.31	2	?	LeF88
RXJ0911+0551	2.80	3.1	$R = 18.0$			3	acc	Bade97
HE1104 − 1805	2.32	3.1	$B = 16.9$	G?	1.66?	2	acc	Wis93
3C297	1.4	2.4	$R = 21.0$	G		2	?	Ham90
Q0142 − 100	2.72	2.2	$R = 16.8$	G	0.49	2	acc	Surd87
PG1115+080	1.72	2.2	$R = 15.8$	G,CL	0.29	4	acc	Wey80
MG0414+0534	2.64	2.1	$I' = 19.3$	G?	1.0?	4E	acc	Hewi92
Class1608+656	1.39	2.1	$R \sim 20$	G	0.63	4	acc	My95
MG1131+045	1.13?	2.1		G?	0.85?	2R	acc	Ham91
MG1654+1346	1.74	2.1	$r = 20.9$	G	0.25	R	acc	Lang89
B1938+666	< 1.0	1.8	$r = 23$	G		4R	acc	Pat94
Q2237+0305	1.69	1.7	$B = 16.8$	G	0.039	4	acc	Huc85
MG1549+3047	> 0.3?	1.7	$R = 23.3$	G	0.111	R	acc	Leh93
HE2149-2745	2.033	1.7	$B = 17.3$	G?	.2 − .5	2	acc	Wis96
SBS1520+530	1.85	1.6	$V = 18.2$			2+1?	?	Cha97
LBQS1009-0252	2.74	1.5	$B = 18.1$	G?	1.62?	2	?	Hewe94
Class1600+434	1.61	1.4	$R \sim 20$			2	acc	Jac95
HST1417+5226	3.41	1.4	$V = 24.3$	G	0.81?	4	acc	Rat95
B1422+231	3.62	1.3	$r = 15.6$	G	0.64?	4E	acc	Pat92
H1413+117	2.55	1.2	$R = 17.0$	G,CL?	1.4? 1.7?	4	acc	Mag88
HST1253-2914		1.2	$V = 25.5$	G		4	acc	Rat95
Class1933+503		1.1	$I > 24.5$	G	0.755	4+5	acc	Syk97
PKS1830-211		1.0		G	0.89	2ER	acc	Jaun91
BRI0952-0115	4.5	0.95				2	?	McM92
MG0751+2716		0.9		G	0.35?	4R	acc	Leh94
J03.13	2.55	0.84	$R = 17.1$			2	acc	Clae96
Q1208+1011	3.80	0.48	$V = 18.1$			2	?	Mag92
B0218+357	0.96?	0.34		G	0.68	2ER	acc	Pat92.2