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Published in:
Scientific World Journal

Link to article, DOI:
10.1155/2013/430870

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Shi, J., & Zhang, C. (2013). On the Set of the Numbers of Conjugates of Noncyclic Proper Subgroups of Finite Groups. Scientific World Journal, 2013, [430870]. DOI: 10.1155/2013/430870
Research Article

On the Set of the Numbers of Conjugates of Noncyclic Proper Subgroups of Finite Groups

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Received 3 August 2013; Accepted 11 September 2013

Academic Editors: J. Hoff da Silva and J. Park

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Let \( G \) be a finite group and \( NC(G) \) the set of the numbers of conjugates of noncyclic proper subgroups of \( G \). We prove that (1) if \( |NC(G)| \leq 2 \), then \( G \) is solvable, and (2) \( G \) is a nonsolvable group with \( |NC(G)| = 3 \) if and only if \( G \cong PSL(2,5) \) or \( PSL(2,13) \) or \( SL(2,5) \) or \( SL(2,13) \).

1. Introduction

In this paper, all groups are assumed to be finite. It seems interesting to investigate the influence of some arithmetic properties of noncyclic proper subgroups on the solvability of groups. In [1], Li and Zhao proved that any group having at most three conjugacy classes of noncyclic proper subgroups is solvable, and a group \( G \) having exactly four conjugacy classes of noncyclic proper subgroups is nonsolvable if and only if \( G \cong PSL(2,5) \) or \( SL(2,5) \). As a generalization of the above result, we showed that any group having at most three conjugacy classes of nonnormal noncyclic proper subgroups is solvable, and a group \( G \) having exactly four conjugacy classes of nonnormal noncyclic proper subgroups is nonsolvable if and only if \( G \cong PSL(2,5) \) or \( SL(2,5) \) (see [2]).

Let \( G \) be a group and \( NC(G) \) the set of the numbers of conjugates of noncyclic proper subgroups of \( G \). We prove that (1) if \( |NC(G)| \leq 2 \), then \( G \) is solvable, and (2) \( G \) is a nonsolvable group with \( |NC(G)| = 3 \) if and only if \( G \cong PSL(2,5) \) or \( PSL(2,13) \) or \( SL(2,5) \) or \( SL(2,13) \).

Theorem 1. Let \( G \) be a group.

(1) If \( |NC(G)| \leq 2 \), then \( G \) is solvable.

(2) \( G \) is a nonsolvable group with \( |NC(G)| = 3 \) if and only if \( G \cong PSL(2,5) \) or \( PSL(2,13) \) or \( SL(2,5) \) or \( SL(2,13) \).

The following two corollaries are direct consequences of Theorem 1.

Corollary 2. Let \( G \) be a group with \( |NC(G)| \leq 3 \). Then \( G \) is solvable if and only if \( |NC(G)| = 3 \) if and only if \( G \cong PSL(2,5) \) or \( PSL(2,13) \) or \( SL(2,5) \) or \( SL(2,13) \).

Corollary 3. Let \( G \) be a group and \( TF(G) \) the set of the numbers of conjugates of nontrivial subgroups of \( G \). Then \( G \) is solvable if and only if \( |TF(G)| \leq 2 \) or \( |TF(G)| = 3 \) if and only if \( G \cong PSL(2,13) \).
Let $G$ be a group and $\mathcal{N}\mathcal{E}(G)$ the set of the numbers of conjugates of nonnormal noncyclic proper subgroups of $G$. Obviously $\mathcal{N}\mathcal{E}(G) \subseteq \mathcal{N}\mathcal{E}(G)$.

Arguing as in the proof of Theorem 1, we can obtain the following result.

**Theorem 4.** Let $G$ be a group. If $|\mathcal{N}\mathcal{E}(G)| \leq 2$, then $G$ is solvable.

**Remark 5.** If we assume that $G$ is a nonsolvable group with $|\mathcal{N}\mathcal{E}(G)| = 3$, we cannot get that $\Phi(G) = Z(G)$. For example, let $G \cong \text{PSL}(2,5) \times \mathbb{Z}_p$, where $p \geq 7$ is a prime. It is easy to see that $|\mathcal{N}\mathcal{E}(G)| = 3$. But $\Phi(G) = 1$ and $Z(G) = \mathbb{Z}_p$.

Let $G$ be a group and $\mathcal{N}\mathcal{A}(G)$ the set of the numbers of conjugates of nonabelian proper subgroups of $G$. Obviously $\mathcal{N}\mathcal{A}(G) \subseteq \mathcal{N}\mathcal{E}(G)$. Arguing as in the proof of Theorem 1, we can also obtain the following result.

**Theorem 6.** Let $G$ be a group. If $|\mathcal{N}\mathcal{A}(G)| \leq 2$, then $G$ is solvable.

### 2. Preliminaries

In this section, we collect some essential lemmas needed in the sequel.

**Lemma 7** (see [3]). Let $G$ be a group. If all nonnormal maximal subgroups of $G$ have the same order, then $G$ is solvable.

**Lemma 8** (see [4]). Let $G$ be a nonsolvable group having exactly two classes of nonnormal maximal subgroups of the same order; then $G/S(G) \cong \text{PSL}(2,7)$, where $S(G)$ is the largest solvable normal subgroup of $G$.

**Lemma 9** (see [5, 6]). Let $G$ be a group having exactly $n$ classes of maximal subgroups of the same order, where $1 \leq n \leq 3$; then one of the following statements holds:

1. Suppose that $G$ is a group with $n = 1$, and then $G$ is a $p$-group for some prime $p$;
2. Suppose that $G$ is a nonsolvable group with $n = 2$, and then $G/\Phi(G) \cong (\mathbb{Z}_3^i \times \text{PSL}(2,7)) \times \mathbb{Z}_2$, where $i, j = 0, 1, \ldots$, and $\mathbb{Z}_2^i \times \text{PSL}(2,7)$ is the semidirect product of the normal subgroup $\mathbb{Z}_2^i$ and the subgroup $\text{PSL}(2,7)$;
3. Suppose that $G$ is a nonsolvable group with $n = 3$, and then $G/S(G) \cong A_6^\times \text{PSL}(2,2), q = 11, 13, 23, 59, 61; \text{PSL}(3,3); U_3(3); S_3(2); \text{PSL}(2,2^f)$, and $f$ is a prime; $\text{PSL}(2,7) \times \text{PSL}(2,7) \times \cdots \times \text{PSL}(2,7)$.

### 3. Proof of Theorem 1

The proof of Theorem 1 follows from the following two lemmas.

**Lemma 10.** Let $G$ be a group. If $|\mathcal{N}\mathcal{E}(G)| \leq 2$, then $G$ is solvable.

**Proof.** Assume that $G$ is nonsolvable. Then by [7, Exercise 10.5.7], all maximal subgroups of $G$ are noncyclic. Let $\mathcal{M}\mathcal{S}(G)$ be the set of the numbers of conjugates of maximal subgroups of $G$. It follows that $\mathcal{M}\mathcal{S}(G) \subseteq \mathcal{N}\mathcal{E}(G)$. Then $|\mathcal{M}\mathcal{S}(G)| \leq 2$.

(1) Suppose that $1 \in \mathcal{M}\mathcal{S}(G)$. Since $G$ is nonsolvable, $G$ must have nonnormal maximal subgroups. Let $M$ be any nonnormal maximal subgroup of $G$; one has $|G : N_G(M)| = |G : M|$. Since $|\mathcal{M}\mathcal{S}(G)| \leq 2$, we know that $G$ has at most one class of nonnormal maximal subgroups of the same order. It follows that $G$ is solvable by Lemma 7, a contradiction.

(2) Suppose that $1 \notin \mathcal{M}\mathcal{S}(G)$. It follows that all maximal subgroups of $G$ are nonnormal. By the hypothesis, $G$ has at most two classes of maximal subgroups of the same order. Since $G$ is nonsolvable and $G$ has no normal maximal subgroups, one has $G/\Phi(G) \cong \mathbb{Z}_2^f \rtimes \text{PSL}(2,7)$ by Lemma 9 (1) and (2), where $i = 0, 1, \ldots$. It is easy to see that $|\mathcal{N}\mathcal{E}(G/\Phi(G)) | = \mathcal{N}\mathcal{E}(G)$ and $|\mathcal{N}\mathcal{E}(\mathbb{Z}_2^f \rtimes \text{PSL}(2,7))| > 2$. It follows that $|\mathcal{N}\mathcal{E}(G)| > 2$, a contradiction.

Thus, our assumption is not true, so $G$ is solvable.

**Lemma 11.** A group $G$ is a nonsolvable group with $|\mathcal{N}\mathcal{E}(G)| = 3$ if and only if $G \cong \text{PSL}(2,5)$ or $\text{PSL}(2,13)$ or $\text{SL}(2,5)$ or $\text{SL}(2,13)$.

**Proof.** The sufficiency part is evident, and we only need to prove the necessity part.

By the hypothesis, $|\mathcal{M}\mathcal{S}(G)| \leq 3$. We claim that

\[ 1 \notin \mathcal{M}\mathcal{S}(G). \tag{1} \]

Otherwise, assume that $1 \in \mathcal{M}\mathcal{S}(G)$. Then $G$ has at most two classes of nonnormal maximal subgroups of the same order. Since $G$ is nonsolvable, one has $G/S(G) \cong \text{PSL}(2,7)$ by Lemmas 7 and 8. It is easy to see that $\mathcal{N}\mathcal{E}(G/S(G)) \subseteq \mathcal{N}\mathcal{E}(G)$ and $|\mathcal{N}\mathcal{E}(\mathbb{Z}_2^f \rtimes \text{PSL}(2,7))| > 3$. It follows that $|\mathcal{N}\mathcal{E}(G)| > 3$, a contradiction. Thus, $1 \notin \mathcal{M}\mathcal{S}(G)$.

Since $|\mathcal{M}\mathcal{S}(G)| \leq 3$, we have that $G$ has at most three classes of maximal subgroups of the same order.

By Lemma 9 (1), $G$ cannot have exactly one class of maximal subgroups of the same order.

If $G$ has exactly two classes of maximal subgroups of the same order, according to Lemma 9 (2), one has $G/\Phi(G) \cong \mathbb{Z}_2^f \rtimes \text{PSL}(2,7)$ since $G$ has no normal maximal subgroups, where $i = 0, 1, \ldots$. Since $|\mathcal{N}\mathcal{E}(\mathbb{Z}_2^f \rtimes \text{PSL}(2,7))| > 3$, it follows that $|\mathcal{N}\mathcal{E}(G)| > 3$, a contradiction.

Thus, $G$ has exactly three classes of maximal subgroups of the same order. By Lemma 9 (3), $G/S(G)$ might be isomorphic to $A_6 \rtimes \text{PSL}(2,2), q = 11, 13, 23, 59, 61; \text{PSL}(3,3); U_3(3); S_3(2); \text{PSL}(2,2^f)$, and $f$ is a prime; $\text{PSL}(2,7) \times \text{PSL}(2,7) \times \cdots \times \text{PSL}(2,7)$.

Thus, $G$ has exactly three classes of maximal subgroups of the same order. By Lemma 9 (3), $G/S(G)$ might be isomorphic to $A_6 \rtimes \text{PSL}(2,2), q = 11, 13, 23, 59, 61; \text{PSL}(3,3); U_3(3); \text{PSL}(5,2); \text{PSL}(2,2^f)$, and $f$ is a prime or $\text{PSL}(2,7) \times \text{PSL}(2,7) \times \cdots \times \text{PSL}(2,7)$, and $f$ is a prime or $\text{PSL}(2,7) \times \text{PSL}(2,7) \times \cdots \times \text{PSL}(2,7)$. It is easy to see that $|\mathcal{N}\mathcal{E}(G/S(G))| > 3$ by [8, 9], which implies that $|\mathcal{N}\mathcal{E}(G)| > 3$, a contradiction. Thus, $G/S(G) \cong \text{PSL}(2,4) \cong \text{PSL}(2,5)$ or $\text{PSL}(2,13)$.  

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Note that \(1 \not\in \mathcal{M}(G)\) and \(|\mathcal{M}(G)| = |\mathcal{N}(G)| = 3\). It follows that \(1 \not\in \mathcal{N}(G)\), so \(S(G)\) is cyclic. We claim that

\[
\Phi(G) = S(G).
\]

(2)

Otherwise, assume that \(\Phi(G) < S(G)\). Let \(M\) be a maximal subgroup of \(G\) such that \(S(G) \nsubseteq M\). Then \(G = S(G)M\). It is obvious that \(S(G) \cap M \subseteq M\). Moreover, \(S(G) \cap M \subseteq S(G)\), since \(S(G)\) is cyclic. It follows that \(S(G) \cap M \nsubseteq G\). Therefore, \(G/(S(G) \cap M) = S(G)/(S(G) \cap M) \times M/(S(G) \cap M)\). Let \(\overline{G} = G/(S(G) \cap M)\), \(\overline{S}(G) = S(G)/(S(G) \cap M)\), and \(\overline{M} = M/(S(G) \cap M)\). By N/C-theorem, \(N_C(S(G)/C_G(S(G))) \leq \text{Aut}(S(G))\). That is, \(\overline{G}/(C_G(S(G))) = \overline{S}(G)/\overline{C}(S(G)) \leq \text{Aut}(S(G))\). Note that \(\text{Aut}(S(G))\) is abelian since \(S(G)\) is cyclic. Moreover, \(\overline{M} \equiv S(G)M/S(G) = G/S(G)\) is a nonabelian simple group and \(G/M \equiv S(G/M) = (S(G)/\overline{S}(G))/(S(G) \cap M)\). Here \(S(G)/M \equiv \overline{S}(G)\). Therefore, one has \(C_{\overline{G}}(S(G))/S(G) = 1 \text{ or } C_{\overline{G}}(S(G))/S(G) = S(G)\overline{M}/S(G)\). If \(C_{\overline{G}}(S(G))/S(G) = S(G)\overline{M}/S(G)\), then \(S(G) \leq Z(\overline{G})\). It follows that \(\overline{S}(G) = S(G) \times \overline{M}\) and then \(M \nsubseteq G\); this contradicts that all maximal subgroups of \(G\) are nonnormal. Thus, our assumption is not true, so \(\Phi(G) = S(G)\).

It follows that \(G/\Phi(G) \cong PSL(2, 5)\) or \(PSL(2, 13)\).

If \(\Phi(G) = 1\), then \(G \equiv PSL(2, 5)\) or \(PSL(2, 13)\).

Next, suppose that \(\Phi(G) \neq 1\). Let \(p\) be any prime divisor of \(|\Phi(G)|\). We claim that \(p \neq 2\). Otherwise, assume that \(p > 2\). Let \(T\) be a subgroup of \(\Phi(G)\) such that \(\Phi(G)/T \cong \mathbb{Z}_p\). That is, \(\Phi(G/T) \equiv \mathbb{Z}_p\). Then \((G/T)/\mathbb{Z}_p \equiv (G/T)/(\Phi(G/T)) = (G/T)/\Phi(G) \equiv PSL(2, 5)\) or \(PSL(2, 13)\). Since \(p > 2\) and Schur multipliers of both \(PSL(2, 5)\) and \(PSL(2, 13)\) are \(\mathbb{Z}_2\), we have that \(G/T \equiv PSL(2, 5) \times \mathbb{Z}_2\) or \(PSL(2, 13) \times \mathbb{Z}_2\). Note that \(|\mathcal{N}(PSL(2, 5) \times \mathbb{Z}_2)| > 3\) and \(|\mathcal{N}(PSL(2, 13) \times \mathbb{Z}_2)| > 3\). It follows that \(|\mathcal{N}(\Phi(G))| > 3\), a contradiction. Thus, \(p \neq 2\), so \(\Phi(G)\) is a cyclic 2-group. If \(|\Phi(G)| = 2^n > 2\), let \(L\) be a subgroup of \(\Phi(G)\) such that \(\Phi(G)/L \cong \mathbb{Z}_2\). Then \((G/L)/\mathbb{Z}_2 \cong (G/L)/(\Phi(G)/L) \equiv G/\Phi(G) \equiv PSL(2, 5)\) or \(PSL(2, 13)\). We have that \(G/L \cong SL(2, 5)\) or \(SL(2, 13)\). Let \(M\) be a subgroup of \(L\) such that \(L/M \cong \mathbb{Z}_2\). Then \((G/M)/\mathbb{Z}_2 \cong (G/M)/(L/M) \cong G/L \cong SL(2, 5)\) or \(SL(2, 13)\). Since Schur multipliers of both \(SL(2, 5)\) and \(SL(2, 13)\) are trivial, we have that \(G/M \cong SL(2, 5) \times \mathbb{Z}_2\) or \(SL(2, 13) \times \mathbb{Z}_2\); this contradicts that all maximal subgroups of \(G\) are nonnormal. Thus, \(|\Phi(G)| = 2\). It follows that \(G \cong SL(2, 5)\) or \(SL(2, 13)\). 

\[
\square
\]

Lemmas 10 and 11 combined together give Theorem 1.

Acknowledgments

The authors are grateful to the referees who gave valuable comments and suggestions. Jiangtao Shi was supported by NSFC (Grant nos. 11201401 and 11361075). Cui Zhang was supported by H.C. Ørsted Postdoctoral Fellowship at DTU (Technical University of Denmark).

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Impact Factor **1.730**

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